MASS FIRE LIFE HAZARD

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MASS FIRE LIFE HAZARD

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FINAL REPORT

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FOREWORD

This report covers the work performed during an investigation under-taken for the U. S. Office of Civil Defense, Department of the Army under the direction of the U. S. Naval Radiological Defense Laboratory.

The study was monitored by Dr. Mathew Gibbons of the Naval Radio-logical Defense Laboratory. Drs. A. D. Mason and F. D. Foley of the Surgi-cal Research Unit, Brooke Army Medical Center, Lt. Col. A. E. Adams, Nuclear Biological Sciences, Medical Field Service School, Brooke Army Medi-cal Center, and Drs. O. T. Benson and D. E. Johnson served as consultants to the program.

The work represents a joint effort of Mr. Andrew J. Pryor, who served as the principal investigator, Dr. Fred W. Bieberdorf and Mr. Calvin H. Yuill. Valuable assistance with animal tests was given by Mr. John Miesse of the Department of Physical and Biological Sciences of Southwest Research Institute.

ABSTRACT

A program was undertaken to define the life hazard in a mass fire environment resulting from nuclear attack. The nature of casualties and hazards in peacetime and wartime fires was reviewed, and experimental efforts to simulate mass fire situations were studied.

This state-of-knowledge review revealed a number of areas in need of further definition regarding the true mass fire life hazard. These areas have been specified and limited experimental studies conducted in two of them in order to define their significance with respect to the overall mass fire life hazard.

SUMMARY

Definition of the mass fire life hazard involves many factors and cannot be stated simply in any quantitative manner. This report is a qualitative description of the hazard as it is known to date.

The first part of this program consisted of examining the life safety problem in various possible fire environments by means of a state-of-knowledge review. It indicates quite clearly the generally recognized hazards. Many investigators have defined these as carbon monoxide, heat, and inadequate oxygen by themselves or in combination depending upon the ventilation conditions. Others conclude generally that the important factors are heat in open areas and carbon monoxide in shelters and that deaths occurred only in those shelters directly exposed to burning or smoldering fuel, sometimes in the form of rubble or debris.

Two recent studies are referenced in which a comprehensive review of the literature relative to combustion products in fires in buildings is presented. Both conclude that carbon monoxide and possibly oxygen deficiency are the primary factors in most building fires. Reference is made to the serious effect of the combination of two or more gases each of which if existing alone may not be harmful.

The interrelationships in the development of carbon monoxide, oxygen deficiency, and other gases, or the possible existence of undetermined synergisms have not yet been defined. Also, medical research indicates the importance of respiratory tract injury as the primary killer of the burn patient, yet there is not sufficient information available to analyze the factors involved in respiratory tract injury. No experimental work has been done on inhalation injuries from combustion products in the upper and middle respiratory tract. The chemical tracheitis is not expected to occur from the inhalation of carbon monoxide, a reduced oxygen atmosphere, or even heat. Noxious gases and smoke are suspected as the cause. Heat may be a factor in causing mucosal injury or enhancing it in the presence of carbon monoxide or other noxious gases.

The life hazards and physiological effects of carbon monoxide, heat, and reduced oxygen have been reasonably well defined for fires in individual buildings; however, a true definition of the mass fire life hazard requires that the effects of these factors in combination be known. The literature reveals very little on this subject that is applicable to the mass fire life hazard.

A limited number of animal experiments were performed to examine the significance of any relationship between carbon monoxide and heat. It is indicated that such a combination may be five to twelve times more lethal than either factor considered separately.

A series of animal experiments is recommended to demonstrate the significance of the noxious gases and smoke in a heated stream of combustion products from the burning of typical building materials. Such a program would either confirm or disprove the preponderance of opinion that carbon monoxide, heat, or anoxia are the main hazards in mass fires.

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I. INTRODUCTION

A.   Background

The history of fire in warfare has been well documented by Rumpf who points to the uninterrupted use of fire in war from "time immemorial."[293] The dropping of incendiary bombs during the air raids of World War II in Germany and Japan again demonstrated the value of fire as an offensive weapon. The mass fires created by some of these air raids literally wiped out large sections of many cities and killed thousands of persons. Damaging as these fires were, however, many persons survived. In general, it is the purpose of this paper to define the life hazard in mass fires with a view to isolating those factors that may be developed to increase the survival rate in any future catastrophe of this nature.

The advent of nuclear bombs in the late stages of World War II demonstrated the power of atomic warfare. One of the most serious consequences was the development of large-scale fires. Since the destructive capability of thermonuclear weapons has increased tremendously since that time, it becomes even more important that all possible avenues of survival be thoroughly explored. Further interest in the subject of this study has developed in recent years as the result of serious fires in individual buildings involving large loss of life. In many instances, it has been recognized that death has been due to causes other than external burns. Since the Cocoanut Grove fire in 1941, medical attention has been directed toward this problem, and more recently regulatory officials have expressed concern over the use of building materials that are suspected of producing smoke or gases as they burn that might interfere with escape and rescue in future building fires. Preliminary research in the latter area has been sponsored by the National Fire Protection Association[243], the United States Public Health Service[385], and the Plastics Industry[95]. All three studies were, in effect, state-of-the-art reviews with a considerable amount of evidence indicating that factors causing loss of life in building fires may be of equal concern in war-induced mass fires.

B.   Scope of Work

The specific objective of this study was to define the threat from nuclear attack fires to people in fallout shelters and elsewhere, and delineate the requirements for life safety in a mass fire environment. Although the investigation was broad and unlimited in scope, the following areas were defined for specific coverage:

(1)   Examining the life-safety problem in various possible fire environments by means of a state-of-knowledge review;

(2)   Suggesting interim guidance and research areas; and

(3)   Initiating supporting investigative laboratory studies and para-
metric analyses.

C.   Approach

The method followed has been to reexamine the evidence presented in
the three studies mentioned above and such additional evidence as can be
found as to the cause of death or injury in fires as it relates to mass fire
situations. More specifically, an attempt was made to answer the question,
"What would be the hazard in a mass fire to the person caught in the open and
the person seeking refuge in a variety of types of shelter?" Past experience
has shown that there exists a large number of conflicts in experimental data
and that much of the experimental work involves methods and techniques differ-
ing to the extent that experimental results frequently cannot be compared.
Therefore, consideration has been given to those specific areas where addi-
tional work is needed to verify results from the past and in some cases to
extend knowledge previously gained in order to define specific situations.

Indicative of the problems involved is the conflict of evidence on what
constitutes a dangerous exposure to heat and other products of the combustion
process. Most of the information available on the hazards of various danger-
ous gases, for instance, relates to eight-hour exposures. To the person
caught in a building fire or caught in the open under air-raid conditions, the
8-hr exposure factor is of little consequence. On the other hand, to
the person seeking refuge in a well-designed shelter, and considering the
fallout situation involved in thermonuclear weapons, it is necessary to con-
sider the situation with respect to a two-week exposure to such gases as may
penetrate into the shelter. The other factor of concern with respect to work
done in the past is the existence of gaps in knowledge of specific components
of the combustion process or of specific gases, both by themselves and in
combination with other gases and effects.

In conducting this study, consideration has been given to individual
building and mass fire situations and to the effects of products of combustion
on individuals. Specifically excluded from this study was the consideration
of the hazards of nuclear radiation and the burns or other factors resulting
therefrom. Also, experimental work has been limited to a very brief explora-
tion of some of the elements involved in the late stages of the program.

In order to familiarize the reader with the organization of this report
and provide him with an understanding of its purpose, the following brief
resumes on the content of each section are relevant.

Section II provides a brief historical account of mass fire experience
to date and is intended to provide the reader with an understanding of the
entire problem, giving him some of the background which established the need
for the research in this report.

Section III is an analysis of the mass fire environment based upon those parameters thought to be most important by persons knowledgeable in the life hazards of fires. This section is a definition of the mass fire environment in general terms and is intended to give the reader an accurate as possible picture of what is to be expected.

Section IV again considers the parameters thought to be most important when analyzed from the aspect of their effects on man. Entitled "Survival Criteria," this section defines the life-safety hazard of each parameter discussed, not only individually but in combination with one another where the information is available.

Section V is a careful examination of mass fires which have occurred in the past. From these a series of conclusions is drawn based on facts or inferences presented relative to causes of death. In addition, this section points up the important differences in mass fires and how the life safety of people within them is threatened by the parameters previously discussed in Sections III and IV.

Section VI is an analysis of the life hazards presented to persons in various shelter situations by a mass fire environment. Life safety is considered in conflagrations and fire storms (with and without fallout) for people in the open, in OCD designated and nondesignated shelters. Also in this chapter, the German shelter experience is evaluated. In addition, the closed shelter which has gained such interest since World War II is also considered for both its internal (heat and CO_2 buildup within) and external hazard.

Section VII reports the results of a series of experimental test fires using Douglas fir. During these tests, the combustion product stream was analyzed for its CO, CO_2, O_2, and heat content. Under these carefully controlled conditions, the only factor varied was ventilation. From these experiments, the ranges of CO, CO_2, heat, and the degree of oxygen reduction (along with their various ratios) may be established with regard to the varying ventilation rates and corresponding time.

Section VIII is a brief outline of an initial series of animal tests designed to demonstrate the significance of certain synergistic actions regarding some of the more common and important parameters expected to be a hazard to life in any mass fire environment. The particular tests completed during this project demonstrated the significance of the synergism between heat and carbon monoxide.

D.   Definitions

Any thorough analysis of life hazard in a physical situation of necessity involves the use of medical terms, many of which may not be clear to all readers. While the use of such terms has been limited, complete elimination of them could not be achieved without unduly increasing the length of this

report. In the interests of brevity and clarity, we list here the definitions of the medical terms used in this report - and also the definitions of a few other special terms used in the report.

ANOXEMIA - Lack of sufficient oxygen in the blood.

ANOXIA - Oxygen deficiency, with consequent disturbance in body functions.

ASPHYXIA - Unconsciousness due to suffocation or interference of any kind with oxygenation of the blood.

CANNULA - An instrument devised to fit various body channels.

CARBOXYHEMOGLOBIN - The compound formed by carbon monoxide with the hemoglobin in poisoning by that gas.

CHEYNE-STOKES RESPIRATION - A type of breathing in which the respirations gradually increase in depth up to a certain point and then decrease; finally, all respiration ceases for half a minute or so and then begins again as before.

CONFLAGRATION - A mass fire with a moving front. Strong winds or topography cause the fire to spread in a particular direction.

CYANOSIS - A dark bluish or purplish color of the skin and mucous membranes, due to insufficient oxygen in the bloodstream. Cyanosis appears when the reduced hemoglobin in the capillary blood is 5 mg or more per 100 cc.

CYANOTIC - Relating to or marked by cyanosis.

DESIGNATED SHELTER - Shelter surveyed, stocked and marked by Office of Civil Defense as a shelter.

DYSPNEA - Shortness of breath; difficult or uncomfortable respiration.

EDEMA - Excessive accumulation of fluid in the tissues, causing swelling.

EPIGLOTTIS - The cartilage in the throat which guards the entrance to the trachea (windpipe) and prevents fluid or food from entering it when one swallows.

EPITHELIUM - The cells lining all the passages of the hollow organs of the respiratory, digestive, and urinary systems.

FIRESTORM - A mass fire with stationary front. Strong inward winds are caused by rising columns of hot gases, and the spread of fire is largely limited to the initially ignited area.

FIREWHIRL - A violent wind devil or cyclonic action of varying size and intensity which occurs within large fires due to the unstable air conditions.

GLOTTIS - The vocal cords and opening between them.

HEMOGLOBIN - The pigment in the red blood cells. It is the substance which carried oxygen to the tissues.

HYPERTHERMIA - Extremely high fever.

HYPERTHERMIC - Producing a high fever.

HYPOXIA - Inadequate oxygen in the lungs and in the blood.

IN VITRO - Within glass; said especially of experiments carried on in test tubes or outside of the living organism.

IN VIVO - Within the living organism: opposed to in vitro.

LARYNX - The voice box, situated between the base of the tongue and the windpipe.

MASS FIRE - A fire which occurs from the merging of several separate fires into a single fire involving a large number of buildings.

NECROSIS - Death of tissue.

NONDESIGNATED SHELTER - Any area used as shelter which has not been surveyed, stocked and marked by the Office of Civil Defense authorities.

NOXIOUS GASES - Injurious, harmful gases.

PHARYNX - The upper expanded portion of the digestive tube, between the esophagus below and the mouth and nasal cavities above and in front.

TOXEMIA - Blood poisoning, the presence in the blood of any pathogenic microorganism.

TRACHEA - The windpipe; the air-tube extending from the larynx to the bronchi.

TRAUMA - A wound or injury, usually inflicted more or less suddenly.

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II. MASS FIRE EXPERIENCE

In September of this year, England will commemorate the 275th anniversary of the Great London Fire. Dramatically described in Samuel Pepys Diary[267], this conflagration wiped out a large section of the old London. It was one of a series of conflagrations that, over the years, has taken a great toll in lives and property.

Records of these early fires are apt to be sparse, if at all existent. It was not until the late nineteenth century that detailed records were made of mass fires. Indicative of the losses involved are records taken from the NFPA Handbook of Fire Protection[245] of which Table 1 is a brief tabulation.

TABLE 1. MASS FIRES IN PEACETIME

City	Year	Life Loss
Chicago	1871	250
Peshtigo	1871	1,052
Boston	1872	13
Baltimore	1904	0
San Francisco	1906	452
Tokyo/Yokahama	1923	91,334
Hakodate, Japan	1934	2,018
Chang Sha, China	1938	2,000
Fukui, Japan	1948	3,000
Chunking, China	1949	2,513

These were peacetimes fires. In some instances, the number of lives lost in comparison to the buildings destroyed was relatively low, reflecting a slow advance of the fire which allowed time for people to escape, often with many of their household goods. The Baltimore fire occurred in the business district on a weekend. Even so, it was remarkable that no lives were reported lost. The San Francisco and Tokyo fires followed earthquakes and covered such wide areas that escape became extremely difficult. Also, it is difficult to separate the casualties caused by the earthquake from those caused by the fire.

The great fires in Japan and China involved highly combustible, closely built dwellings that invited such rapid fire spread as to render escape extremely difficult.

The potential for mass fires in today's cities still exists, but to a much lesser extent than formerly. Fire-resistive construction is now required

in the heavily built-up areas so that the risk decreases as older buildings are replaced by new. Greater separation between buildings, wider streets, and better trained and better equipped fire departments add to the relative safety of our cities today.

What is said above applies to peacetime mass fires. The methods used in subduing the enemy in World War II demonstrated the value of fire as an offensive weapon system. It was used with extreme effect in World War II. The statistics compiled by Lommasson[191] and presented here as Table 2 serve as a grim reminder of the destructive potential of fire used as a weapon of offense.

TABLE 2. SUMMARY OF GERMAN AND JAPANESE AIR RAID
EXPERIENCE DURING WORLD WAR II

City	Lives Lost	Percent of Population	Buildings Destroyed	Area Burned, sq mi
Tokyo	84,000	1.2	300,000	15.8 (total loss)
Hamburg	42,000	2.4	300,000	4.5 (total loss) 12 (heavy damage)
Kassel	8,700	3.8	33,000	2.9 (total loss)
Darmstadt	8,100	7.4	22,000	1.5
Hiroshima	70,000	28.0	68,000	4.4 (firestorm area)
Nagasaki	40,000	17.0	21,000	0.049 (fire only) 0.864 (fire and blast)

Unquestionably, casualties were greatly reduced due to partial evacuation of cities prior to the war action. Essential workers, however, were needed in target areas and, in some instances, particularly in the German cities, were afforded some protection by air-raid shelters. In Hamburg alone, some 240,000 people survived the extremely heavy air raids in massive, bunker type shelters[98]. Other types of shelters were not as successful, and many thousands lost their lives in what they had thought would be relatively secure area. In other instances, masses of people took refuge in open spaces, often with mass casualties resulting. The reasons for the heavy casualties in mass fires are the primary concern of this study, and all of the possibilities will be examined in the following sections.

The techniques of defining causes of death in fires today are not sufficiently developed to assure positive meaning to various types of analyses that may be conducted. For instance, if a body has reddened lips and skin, a rule of thumb diagnosis is "death by carbon monoxide." More sophisticated studies have revealed other causes of the reddening. Some studies have uncovered circumstances[280] where traces of carbon monoxide poisoning

have been obliterated by other exposures. In wartime situations or mass fire situations where the fight for survival is of prime concern, individuals are not apt to be present having a scientific interest and the equipment necessary to make measurements of temperatures, possible toxic gases, types of smoke, oxygen levels, and other factors that may present a hazard to life. Thus, the present effort has been to scan in detail the available records for clues as to what might have happened. This, in combination with current studies of the reaction of animals and people exposed to fire conditions and autopsies conducted on those who have succumbed to such exposures, provide sources of information on which to assess the mass fire life hazard.

Certain other historical events provide further light on the subject. Extreme conditions resulting from crowding too many people into too small a space with excessive heat developing were demonstrated in the incident known as the "Black Hole of Calcutta." Here, in 1756, 145 men and one woman are reported to have been taken prisoner and thrown into a cubicle 18 ft long, 14 ft high and 10 in. wide[198, 249]. The cumulative body temperature caused a rise in ambient temperature and emotional stress to a point that only twenty-two men and the woman were alive the following morning. In more recent years, the Cocoanut Grove Nightclub fire in Boston in 1942 involved 489 deaths and more than 166 injuries[24]. Such fires as this, together with other tragic fires, provide the incentive for more intensive research in fire prevention on the one hand and in medical treatment of burn injuries on the other. Many of the resulting data are applicable to the life hazard in mass fires.

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III. MASS FIRE ENVIRONMENT

A.   General

The mass fire environment is an extremely complex and changing phenomenon. It could be said that the mass fire environment will be hot and smoky, have changing wind velocities, and contain a conglomeration of combustion products. To consider the situation analytically, we must know how hot for how long, how much smoke, what are the wind velocities, and what are the concentrations and locations of the combustion products present and their persistence.

Discussion of any one of the parameters in a mass fire environment will show that there is an interrelationship between it and the others; for example, the amount of carbon monoxide is related to the oxygen content, and these are both related to the wind speed. Perhaps more important is the relationship of the fuel and its chemical composition with the parameters of this environment. When considering a fixed point within a mass fire environment, one recognizes the need of an adequate definition of terms in showing the interrelationships of the parameters involved.

Numerous investigators have recognized these difficulties and expressed their concern as to the value of extrapolating the results of experimental work to other fires. Each experimental fire presents its own particular set of conditions, and the results obtained do not always agree with what has been recorded in others. Nevertheless, it should be possible to define within some range the important life-safety parameters within a mass fire.

This section is concerned only with the mass fire environment and the levels of toxic gases, heat, and smoke to be found therein. The meaning of the levels of concentrations of these gases, heat, and smoke with respect to life safety is discussed in detail in Section IV.

B.   Hazards of Mass Fire Environment

1.   Convective Heat

The time-temperature history within burning buildings during peacetime has been of much interest in the past because of its direct relationship to the structural integrity and the safety of personnel within and around the burning buildings. Present building codes reflect this interest in the requirement for structural elements to withstand different amounts of exposure to a standard fire.[240] The ASTM E119 time-temperature curve[8] has been developed as a result of actual building burns, and it has been found to be fairly representative of the interior temperatures (if not lower) as measured in burning buildings by many investigators since its establishment.[37, 307, 311] This curve, shown in Figure 1, is in no way meant to be
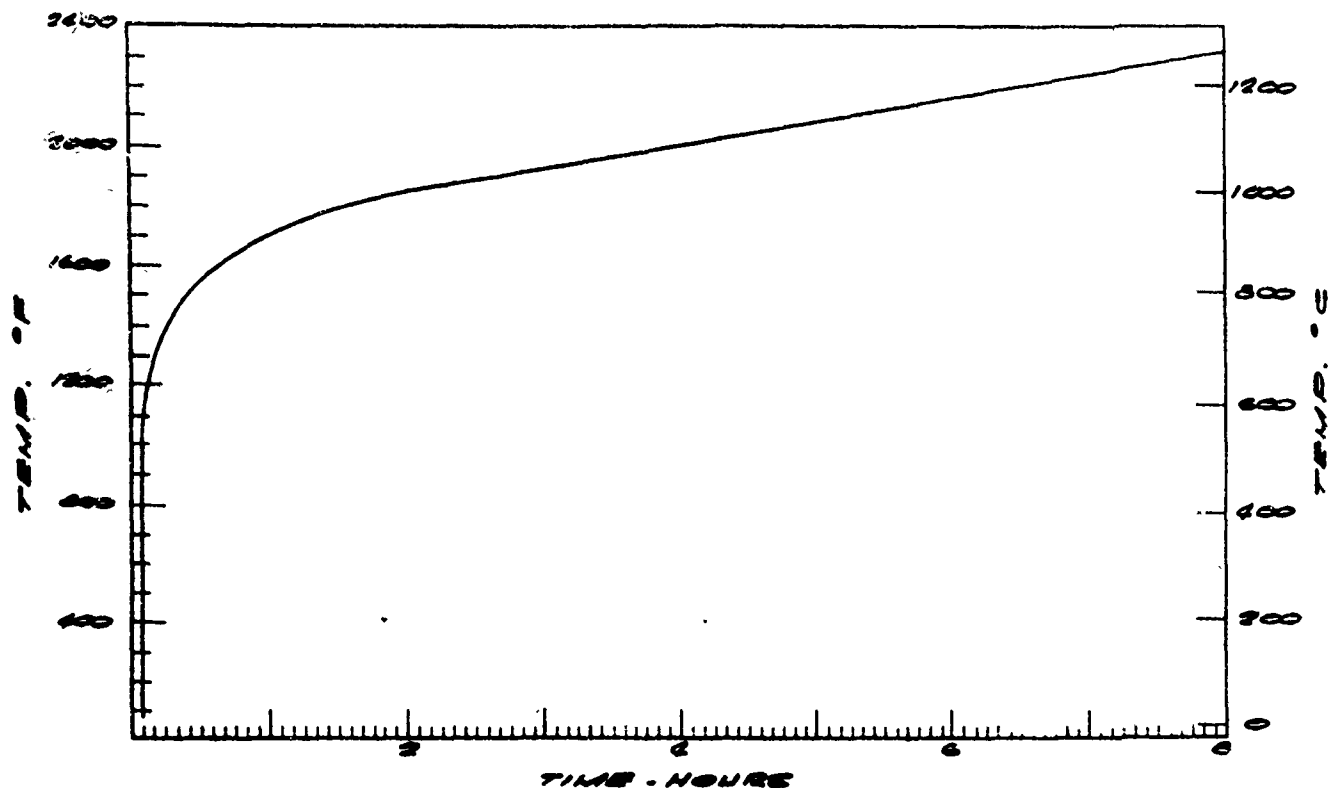
Source: See Ref. (8)

FIGURE 1. STANDARD TIME-TEMPERATURE CURVE

representative of the fire conditions expected within a mass fire, but it does represent the temperatures to be expected within a fully involved burning structure.

The temperatures or heat flux to be expected within a mass fire are not precisely defined as yet. There is considerable interest in this definition, and much is presently being done in an attempt to better define the heat flux within a mass fire.[82]

The heat flux as measured in any fire can only be defined for that particular fire and at a particular measuring point. There may be questions regarding its meaning or its relationship to other fires or even to other points within the test fire monitored. Experimental fires to date have been small, the largest being 40 acres in size. Some investigators have stated that mass fires require the involvement of at least 640 acres (1 square mile).[37] Fires are complex, and no one fire may be typical; that is, there is no evidence to reflect the similarity or reoccurrence to be expected with regard to any of the parameters of interest. For these reasons, it is very difficult if not impossible to extrapolate from these fires. This is pointed out quite well in a report by Countryman[82] in which he states:

"In general then, one must conclude that although there exists a considerable body of knowledge about the characteristics of small fires and of fires burning under normal conditions, there is a dearth of quantitative information concerning large and intensive fires."

These questions are valid; however, it should still be possible, by means of a series of tests, to determine the "range of temperatures" to be expected in various locations within a fire. Test data to accomplish this will be examined below. For civil defense purposes, the area of the average and the upper range temperatures would be of greatest interest.

In this regard, the upper range must be looked at carefully in order to determine its duration and frequency of occurrence within the mass fire environment as a whole. For example, temperatures of 1925°C (3500°F) that occur only over small areas at a very few specific locations and for very short periods of time are not nearly as significant as temperatures of 1260°C (2500°F) which occur over much larger areas at many locations for longer periods of time.

An additional factor to consider is the significance of the temperature or heat flux differences. For example, to a person caught out in the open, temperatures of 1260°C (2500°F or above) are immediately fatal. The difference, therefore, between 1260°C and 1925°C is academic regarding survival. An upper "range" that has been recorded in the immediate flaming fire zones of burns by various experimenters has been in the 980° to 1315°C (1800° to 2400°F) range.[37, 274] A lower range has clearly been shown by experiment to be in the range of 815° to 980°C (1500° to 1800°F).[307, 311] These burns would have to be regarded as small in relation to a mass fire. Burns conducted by the U. S. Forest Service have indicated the possibility of much higher temperatures approaching 1650°C (3000°F). These have been recorded in relatively small burns where the burning rate or violence of the fire was high.[37, 274] This approaches the temperature obtained when wood is burned under ideal conditions [1800°C (3272°F)][52].

The following pages present a brief summary of these experimental burns together with their maximum recorded temperatures. Professor H. Hottel of the Massachusetts Institute of Technology suggested at the Fourth Annual Office of Civil Defense Fire Research Contractors Conference in Pacific Grove, California, in March 1966, that perhaps a simple method of determining a fire's severity would be to define its maximum temperature and a corresponding time during which the fire was at or above some predetermined burning rate or some minimum temperature. In this summary, the maximum recorded temperatures, along with the times during which temperatures of one-half the maximum were recorded, are reported.

It is indeed surprising to glance through this summary and note that a number of experimenters have utilized equipment which proved incapable of accurately recording the maximum temperatures in their experimental

burns. For this reason, the maximum attainable temperature in such burns has yet to be recorded.

The tests listed here were sponsored by the following organizations:

Office of Civil Defense Mobilization

Briones Burn
Camp Parks Burn
El Cerrito Rubble Probe Test
Los Angeles Tests
Richmond Test No. 1
Richmond Test No. 2

Office of Civil Defense

U. S. Forest Service Burns
Test Fire 380-4-63
Test Fire 380-6-63

Los Angeles Fire Department

Los Angeles School Burns

Division of Building Research, Material Research Council of Canada

St. Lawrence Burns

Briones Burns[37]

Eleven windrows of trees and brush totaling about 900 tons "oven-dry weight" on an area of nine acres were ignited in sequence.

Maximum Temperature	Thermocouple Locations
1065°C (1950°F) >540°C (>1000°F) for 50 min	1 ft above grade and 3 ft inside burning windrow
870°C (1600°F) >430°C (>800°F) for 50 min	2 ft above grade and 3 ft inside burning windrow
315°C (600°F) >150°C (>300°F) for 40 min	at grade and 1 ft and 2 ft; above grade 5 ft outside edge of burning windrow
150°C (300°F) >65°C (>150°F) for 60 min	at grade and 1 ft and 2 ft; above grade 25 ft from nearest windrow

Camp Parks Burn[37]

Seventy-four simulated houses, each approximating 6000 lb of wood, were ignited simultaneously. The following temperatures were recorded:

Maximum Temperature	Thermocouple Locations
>1315°C (>2400°F) (TCPL failure at 5 min)	2 ft above grade in rubble-free pile in center of burning area
>1430°C (>2600°F) (TCPL failure at 8 min)	1 ft above grade in rubble-free pile in center of burning area
930°C (1700°F) >455°C (>850°F) for 15 min	1 ft above grade in rubble pile in center of burning area
150°C (300°F) >65°C (>150°F) for 30 min	1 ft and 2 ft above grade and approximately 10 ft of horizontal distance from free burning fires located in center of burning area
260°C (500°F) >120°C (>250°F) for 10 min	in front of shelter entrance located approximately 10 ft from burning rubble piles in center of burning area

El Cerrito Rubble Probe Test[37]

An old municipal building constructed of thick concrete with stucco and brick covered walls was ignited and allowed to burn freely. Rubble temperatures were recorded at three locations and reported as follows:

Approximate Time after Start (hr)	Temperatures (°F)		
	1	2	3
4.5	900	1290	-
6.0	580	550	-
6.7	360	480	-
9.7	225	270	890
21.3	80	80	1890

Los Angeles Tests[37]

The first fire consisted of 2 X 4 mill ends scattered to a depth of about 2 ft throughout a room in a vacant school. Fire was ignited in one corner and extinguished at 17 min when the floor above was endangered (long before the fuel at the base of the pile could be burned).

Maximum Temperature	Thermocouple Locations
650°C (1200°F)	recorded at 6-ft and 10-ft level at 17 min
>315°C (>600°F) for 7 min	extinguishment started at this time

In the second fire, the room was loaded with lath and pallets and ignited at a number of points around the outer edges. This was allowed to burn for 12 min before extinguishment was started.

Maximum Temperature	Thermocouple Locations
>980°C(>1800°F)	temperature at 10-ft level exceeded 980°C
>480°C (>900°F) for 8 min	(1800°F) twice during the 12-min burn

Richmond Test No. 1[37]

A two-story, four-apartment building, measuring 50 × 28ft, stucco covered, gypsum wallboard interior, oak floors and scrap lumber to simulate furnishings was ignited and permitted to burn completely.

Maximum Temperature	Thermocouple Locations
1538°C (2800°F) >760°C (>1400°F) for 10 min	recorded at 1 ft above grade
925°C (1700°F) >454°C (>850°F) for 75 min	recorded at 2 ft above grade
1260°C (2300°F) >620°C (>1150°F) for 80 min	recorded at grade

Richmond Test No. 2[37]

Two single-story wood houses, one measuring 50 × 22 ft and the other 24 × 18 ft, about 7 ft apart at their nearest corners were ignited and allowed to burn completely.

Maximum Temperature	Thermocouple Locations
>1370°C (>2500°F)	recorded at grade and at 1 ft and 2 ft above
TCPL failure at 25 min	grade inside houses

U. S. Forest Service Burns[82, 274]

Test Fire 760-2

Thirty-six piles of pinion pine each weighing 20 tons ("over-dry weight") and measuring 47 ft square by 8 ft high were simultaneously ignited over an area of 4-1/2 acres.

Maximum Temperature	Thermocouple Locations
>1455°C (>2650°F) (TCPL failure)	recorded at two piles (one peripheral) within 2-1/4 min from ignition
1090°C (2000°F) >540°C (>1000°F) for 10 min	recorded at 20-ft height in center of fire area
260°C (500°F) >120°C (>250°F) for 35 min	recorded at 20-ft height in aisles just inside peripheral piles
760°C (1400°F) >370°C (>700°F) for 15 min	recorded at 20-ft height in aisles just inside peripheral piles

Test Fire 460-14

A 40-acre plot containing 324 simulated houses, each approximating 20 tons of "dry weight" pinion pine, was ignited.

Maximum Temperature	Thermocouple Locations
760°C (1400°F) >370°C (>700°F) for 5 min	recorded in flame zone

Test Fire 380-4-63[82, 274]

Maximum Temperature	Thermocouple Locations
>1430°C (>2600°F) >700°C (>1300°F) for 16 min	recorded 15 ft above fuel bed
1065°C (1950°F) >480°C (>900°F) for 1 hr	recorded at middle and top of fuel bed

Test Fire 380-6-63[82]

In a fire designated as 380-6-63, the temperature profile at three points with respect to time were as follows:

Maximum Temperature	Thermocouple Locations
140°C (~290°F) >65°C (>150°F) for 52 min	recorded at a distance of 6 ft from the fire
80°C (~170°F) >30°C (>85°F) for 70 min	recorded at a distance of 53 ft from the fire
43°C (~110°F)	recorded at a distance of 200 ft from the fire

Los Angeles School Burns[195, 196]

Several tests were conducted with 1400 lb of pallets as fuel burned in various areas of a large school building. High temperatures were reached throughout the test fire, and extinguishment was initiated either manually or by automatic sprinklers at or before 20 minutes. High temperatures reached on the average were well above 540°C (1000°F) and in many cases above 700° or 760°C (1300° or 1400°F). Some went above 816°C (1500°F). These maximums were reached at approximately 10 min after ignition with temperatures above half the maximum value for 12 to 14 minutes.

A second series of tests was conducted with varying amounts of fuel such as paper, rags, and wood. The fuel was ignited and allowed to burn free for varying periods of time until extinguishment was initiated manually. Maximum temperatures of 816°C (1500°F) or higher were common with wood cribs (200 to 350 lb) burned in areas of combustible interior finish. These high temperatures were reached within 2 min of ignition and continued well above 540°C (1000°F) for the duration of the test - 10 to 15 minutes.

St. Lawrence Burns[311]

Six abandoned dwellings, three with relatively incombustible linings and three with relatively combustible linings, were burned with wood cribs as simulated furnishings.

Maximum Temperature	Remarks
>955°C (>1750°F) >470°C (>875°F) for 26 min until TCPL failure	recorded in houses with combustible linings
>955°C (>1750°F) >470°C (>875°F) for 18 min until TCPL failure	recorded in houses with (relatively) incombustible linings

a.   Other Experiences

In a U.S. Forest Service Research Note[274], C. W. Philpot concludes that temperatures in a mass fire may be in excess of 1455°C (2650°F). This is supported by Broido and McMasters[37]; however, it should be noted that both these maximums were recorded on thermocouples that failed. As a result of these failures, the maximum temperatures reached were not recorded in those fires. A portion of Philpot's conclusions concerning the maximum recorded temperatures reads as follows:

"Temperatures of 2650°F were recorded by bare thermocouples in and above the flame zone on a large field test fire. Even higher temperatures are probable, judging from such evidence as the melting of steel and chromel wire and

the light yellow-orange areas of flame appearing in certain areas of the fire. This means that the 1500°F measured by Bruce, Pong, and Fons (1959), the 1800°F predicted by Byram (Davis 1959), the 1500°F reported by Lindenmuth and Byram (1948), and 2000°F predicted by Vehrencamp (1956) are low for mass fire situations. These values relate to much lighter fuel loadings than in the present study. Our readings are more in agreement with the 2600°F recorded by Broido and McMasters (1960). Therefore, it may be necessary to use values of 2600°F or higher when trying to describe the thermodynamics of large fires."

In Reference (350), police engineers in Hamburg estimated that temperatures within the firestorm area went as high as 800°C (1472°F). Leutz, who was in Hamburg at the time of this fire, estimates that the temperature of the firestorm was as high as 1400°C (2552°F) (see Fig. 2). It is not
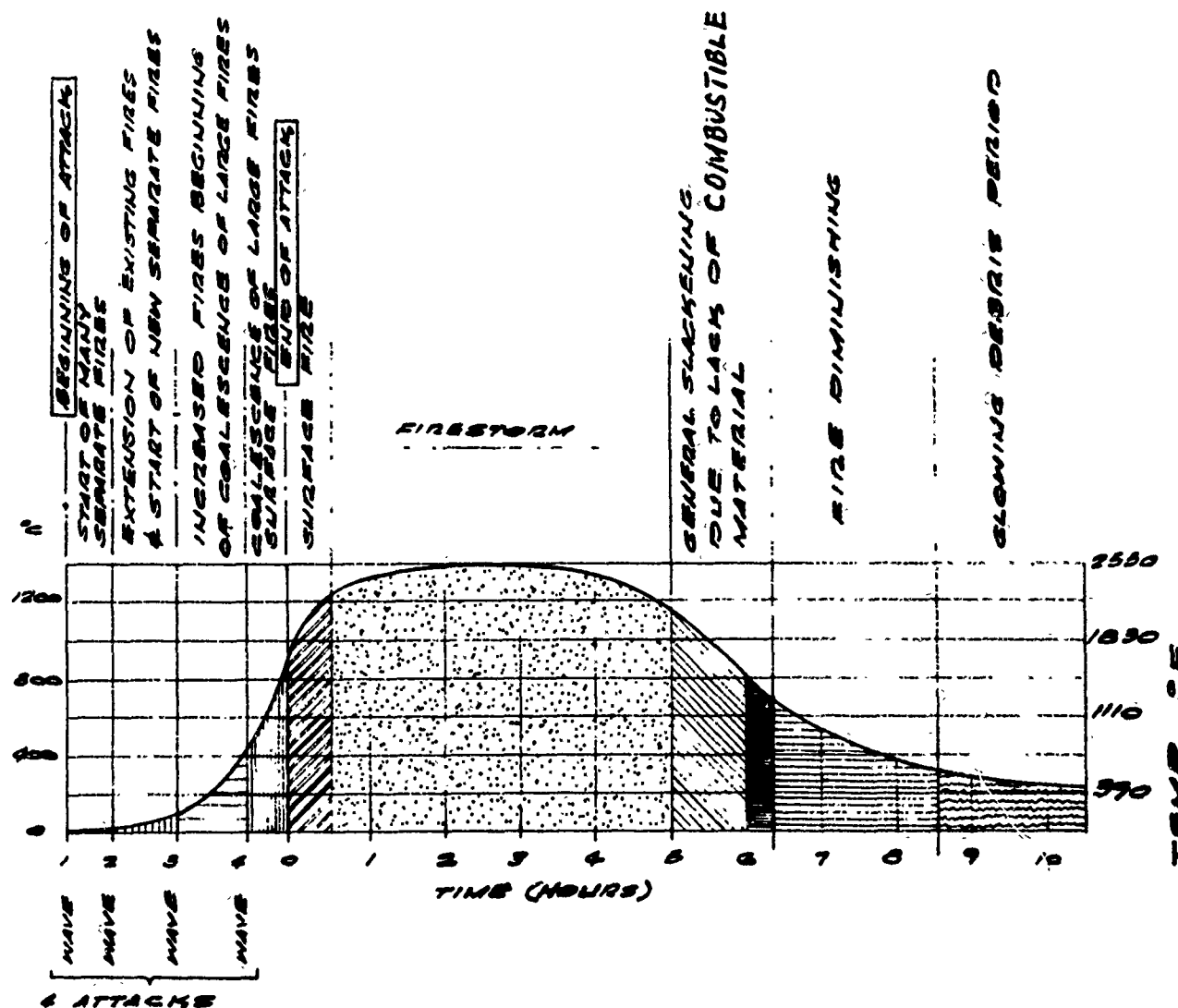
Source: See Ref. (182)

FIGURE 2. TIME-TEMPERATURE HISTORY OF HAMBURG FIRE

known just where these temperatures were estimated to have been encountered. However, Leutz states that "It can be assumed, from both the experiences of World War II and fire experts, that a temperature of from 300° to 400°C exists for a period of about five or six hours on a shelter roof slab"(182) (see Fig. 3). Thus, it appears that Leutz is making reference to the lower
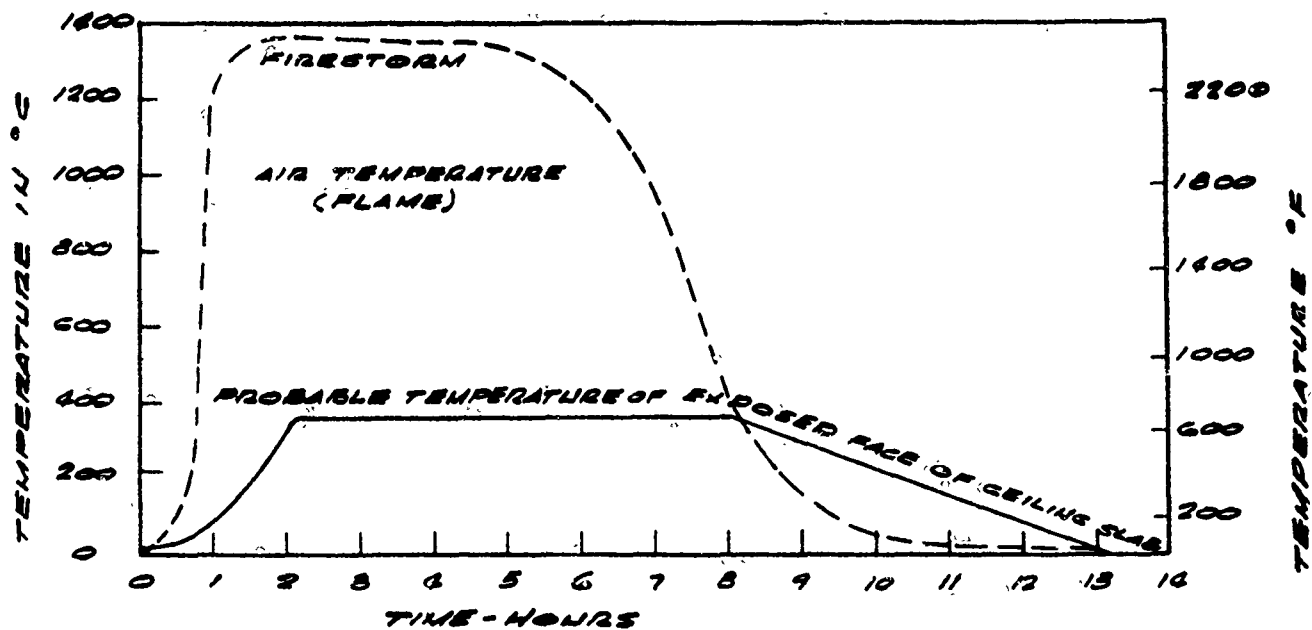
Source: See Ref. (182)

FIGURE 3. TEMPERATURES OF THE FLAME AND EXPOSED
FACE OF SHELTER CEILING SLAB

temperatures to be expected out in the open as opposed to temperatures within burning buildings or directly within the fire area.

b. Summary

Temperatures well in excess of 1090°C (2000°F) can be expected within, immediately above, and downwind of well-involved burning structures. Maximum temperatures in natural free-burning fires have yet to be recorded; however, they are expected to be around 1650°C (3000°F) in those fires which burn intensely with a high rate of fuel consumption. Temperatures drop off rapidly with distance from a burning structure particularly on the upwind side and remain at their maximums only for short periods.

Fuel that is free standing burns faster and hotter because of its free access to oxygen. Fuel that has fallen and been piled with rubble will reach its temperature peak much later and burn longer. In the El Cerrito burn, the rubble was probed with instruments at intervals for one day following ignition, and temperatures as high as 1030°C (1890°F) were recorded 21 hr after ignition. The average temperature reading after fifteen measurements taken throughout the 21-hr period was approximately 315°C (600°F).

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2. Thermal-Radiant Energy

Heat from a fire occurs in three forms of energy: convective, radiant, and conductive. The radiant energy received at any point around the fire is a function of the temperature of the fire, its emissivity and the distance from it. Considering that temperatures in burning buildings frequently reach 1090° C (2000° F) and sometimes 1315° C (2400° F) or higher, radiant energies reach levels which are significant to the mass fire life hazard.

In general, the intensity of radiation, I, emitted from a hot body is related to its absolute temperature, T, according to the law

$$I = E\sigma T^4 \tag{1}$$

where

E is emissivity, less than or equal to unity

σ is the Stefan-Boltzmann constant

T is the absolute temperature

The emissivity of a surface has a maximum value of unity, and a small opening in the wall of a uniformly heated enclosure having opaque walls tends to be blackbody radiation. Calculations indicate that most flames greater than 15 in. in depth will have an emissivity value approaching unity. With this information and the temperature ranges previously discussed, the ranges of radiant energy which may be emitted within a mass fire environment can be predicted.

The radiation falling on any surface is inversely proportional to the square of the distance between it and the emitting source if the emitting source is a point source. If the source of energy is not a point but an extended area (or volume), then this simple law does not hold and the intensity received at any point depends on the shape and orientation of the radiator with respect to the receiver. A procedure for determining radiation levels has been established by Law[176], and McGuire[213, 214].

Thermal radiation is considered by many[52, 75, 366] as the most important source of fire spread within urban areas. There is no question that thermal energies strong enough to ignite exposed structures can be generated from considerable distances by burning structures. A recent U. S. Forest Service burn of simulated one-story, two-bedroom frame houses created thermal radiant energies of approximately 0.5 cal/cm^2-sec at distances of 100 ft from the fire's edge.[346]

Spontaneous ignition of wood requires intensities of 0.8 cal/cm^2-sec, and pilot ignition requires approximately 0.4 cal/cm^2-sec. Spontaneous ignition usually occurs within 2 min after exposure or not at all, but the time for pilot ignition in the open can be longer, and near the threshold level of radiation, heating times of the order of 10 min are needed before ignition can take place.[176]

Two levels of peak radiation intensity are proposed by Law[176], one severe and the other moderate. The temperature of the fire depends on the rate of burning, and fires are considered as divided into two types: (1) those in which the ventilation is restricted and the rate of burning depends on the size of the window; and (2) those in which the window area is comparable to the floor area and the rate of burning depends on the fire load, its surface area and arrangement, and not on the window area.

The first type of fire may be said to be ventilation controlled and the second type fuel controlled. The ventilation controlled fires tend to have a limiting value of less than 1100°C (2000°F) which corresponds to a theoretical maximum radiating level of 4 cal/cm^2-sec. Each of these two types of fires is considered under severe conditions (i.e., maximum heat release) and under moderate conditions which are defined as a fire load of less than 5 lb/ft^2. As previously mentioned, the severe case in each type of fire tends to an upper limit of 4 cal/cm^2-sec, and the moderate case, as mentioned, corresponds to a radiation intensity of 2 cal/cm^2-sec.

In the more severe cases where room temperatures reach 1370°C (2500°F) or higher, the radiant intensities can increase to 10 cal/cm^2-sec. The theoretical radiation intensity of a blackbody at 1650°C (3000°F) approaches 20 cal/cm^2-sec.

The highest radiation level recorded during the St. Lawrence Burns[311] was 1.25 cal/cm^2-sec at a distance of 15 ft from the burning structure. The U. S. Forest Service has recorded radiation intensities of 0.2 cal/cm^2-sec at distances of 90 ft from the burning fuel[82]. Levels as high as 0.6 cal/cm^2-sec were recorded in another fire at a distance of 100 ft from the burning fuel.[346]

To date, little experimental work has been accomplished to better define the radiant energies to be expected at varying distances from burning structures.

Since the radiation intensity is directly proportional, at any one point, to the fourth power of the absolute temperatures [see Eq. (1)], the radiation will increase very quickly to its peak with the fire and fall off quickly as the fire dies. Of all three modes of heat transfer, radiation has the shortest response time.

3. Conductive Heat

In any mass fire situation, there will be rubble and debris, and this may result in one of two ways. Structures may first be levelled by forces such as earthquakes, overpressures resulting from high explosive bombs, or even thermonuclear weapons. Ignition frequently follows, and the rubble continues to burn. Under other circumstances, structures may be ignited while standing free and then collapse as a result of weakening by the fire.

Experience in Germany indicates that there was a considerable amount of hot debris from both causes throughout Hamburg, Dresden, and other cities. In many cases, the shelters covered by burning-smoldering debris could not be entered for days and sometimes even weeks after the raids.[350] The degree of heat and the length of time it existed in these debris piles is unknown.

4. Carbon Monoxide

Carbon monoxide is one of the oldest known poisons. Carbon monoxide is a product of both thermal decomposition and the combustion of carbonaceous matter and has long been recognized as a hazard to life. The amount of carbon monoxide produced in a fire is variable and depends on the chemical composition of the fuel, amount of oxygen present, the temperature in and around the combustion zone and the time factor.[99, 100]

As with most toxic gases, carbon monoxide has been considered as an industrial poison. Only in very recent years has attention been given to toxic gases developing during fires. Because of its relatively high toxicity, it has been monitored in many of the experimental burns, and concentrations of varying degree have been reported.

The ensuing discussion of carbon monoxide and the percentages which can be expected within a mass fire can perhaps best be presented by separating the experimental work to date into two categories: (1) that work which has been done with experimental fires and the monitoring of carbon monoxide directly above or adjacent to the burning fuel or even in the same structure, and (2) that work which has been done with monitoring of carbon monoxide outside of burning structures or at relatively greater distances from the burning fuel. Some experiments of this type are reviewed in detail in this section.

As in the previous section on heat, the data on carbon monoxide will be discussed in ranges rather than precise concentrations at specific moments at a particular location.

a. Carbon Monoxide Monitored within Burning Structures and Directly Above or Adjacent to Burning Fuel

(1) Kingman, et al.

An interesting series of tests was conducted by Kingman, et al.[169], in which oxygen (O_2), carbon dioxide (CO_2) and carbon monoxide (CO) concentrations were monitored on the second floor of two houses which were both fitted out with simulated furniture and ignited on the first floor. One house had an interior finish of fiber insulating board and the other had plasterboard lining. The results of these tests are presented in Table 3 and plotted in Figure 4.

TABLE 3. ANALYSIS OF THE ATMOSPHERE IN BURNING HOUSES

Test 1: Fibre Insulating Board*				Test 2: Plasterboard Lining*			
Time, min	Gas Composition, % (vol)			Time, min	Gas Composition, % (vol)		
	O_2	CO_2	CO		O_2	CO_2	CO
Room 1: door closed				Room 1: door closed			
0	20.8	nil	nil	0	20.8	nil	nil
3	20.8	nil	nil	3	20.4	0.1	0.6
6	15.6	0.4	0.9	6	20.1	0.1	1.2
9	15.6	1.5	0.7	12	20.3	0.3	0.4
12	1.8	16.7	1.3	15	20.2	0.2	0.5
15	0.8	0.8	10.4	18	19.4	1.3	0.8
				24	15.6	5.2	1.0
				27	15.4	4.4	0.9
				35	0.4	19.6	0.9
Room 2: door open				Room 2: door open			
0	20.5	0.4	nil	0	20.6	0.2	nil
3	19.9	0.7	0.3	3	19.2	1.3	nil
6	3.6	12.4	0.5	6	18.5	2.2	0.5
9	0.5	17.8	1.4	12	17.2	2.6	0.3
12	1.6	17.8	19.8	15	16.6	3.6	1.1
15	0.3	17.3	12.3	18	16.4	4.0	1.0
18	0.3	9.2	16.7	21	15.6	4.4	0.8
				24	19.7	0.9	0.8
				30	0.2	19.8	3.8
				35	9.9	10.9	1.6

*In both tests, rooms 1 and 2 are on the second floor.

LEGEND:
- O = OXYGEN
- △ = CARBON MONOXIDE
- —— = DOOR CLOSED
- ---- = DOOR OPEN
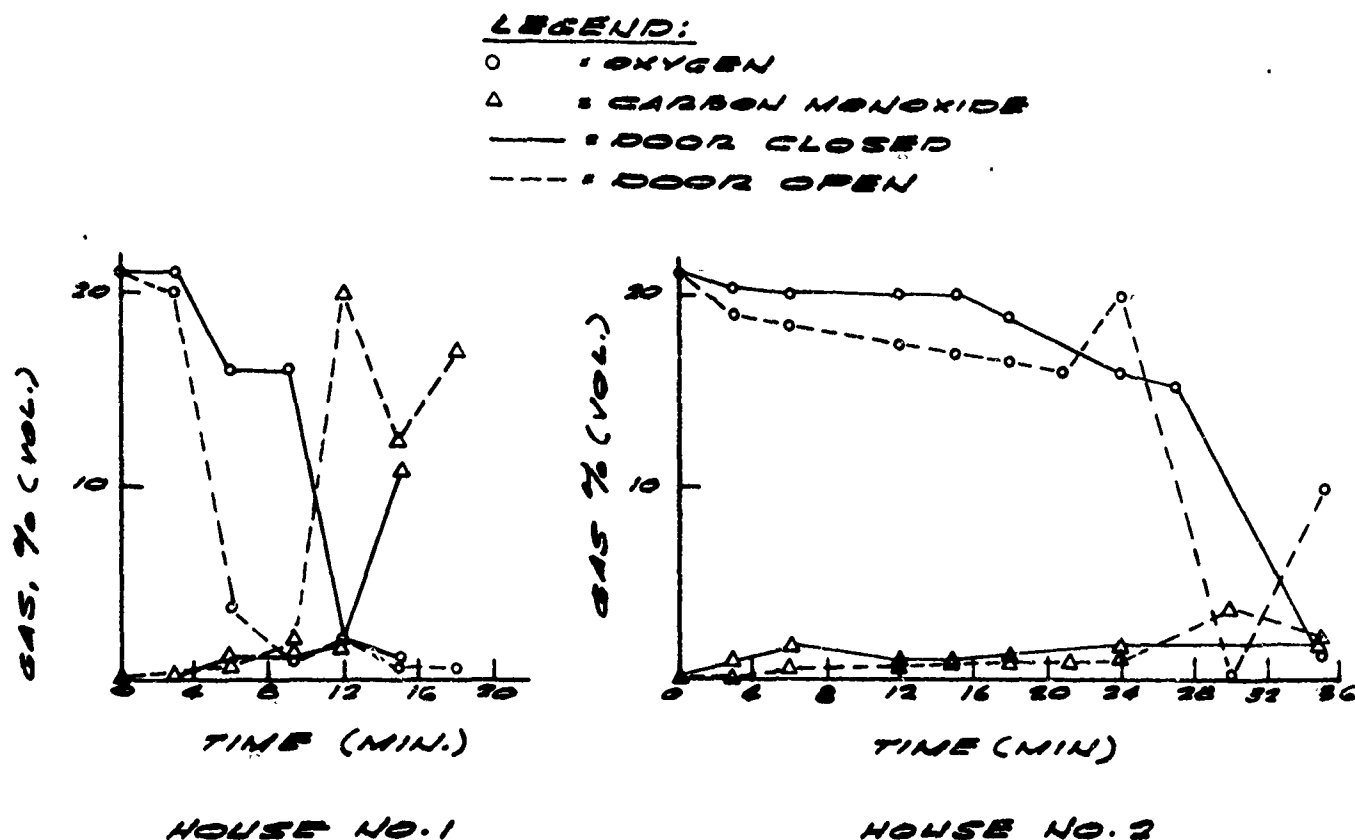
HOUSE NO. 1   HOUSE NO. 2

Source: See Ref. (169)

FIGURE 4.   VARIATIONS OF OXYGEN AND CARBON MONOXIDE IN FIRES

In House No. 1, the carbon monoxide concentrations went from 0.5 percent at 6 min to well over 10 percent at 15 minutes.   The average recorded percentage over the 18-min recording period in Room No. 2 was above 7 percent.

In House No. 2, the carbon monoxide concentrations reached 0.5 percent at 3 to 6 min and varied between there and 3.8 percent for the 30-min test duration for an average of 0.85 percent.   Note the fact that there is very little difference in the concentrations in the open and closed rooms in the second test compared to the differences in the first.

(2)   Forest Products Laboratory[46]

In a series of six burn-out tests conducted by the Forest Products Laboratory reported by Bruce[46], various room interior finish materials were tested.   The room measured 8 ft × 12 ft and simulated furniture (sweetgum lumber, burlap, wood shavings, etc.) was used.   Carbon monoxide concentrations were monitored in three of the six tests (see Table 4).

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TABLE 4. ANALYSIS OF THE ATMOSPHERE IN BURNING ROOMS

Time, min	% CO by Volume		
	Test 1 - Fibre Insulation Board (Unfinished)	Test 2 - Fibre Insulation Board (Finished)	Test 3 - Gypsum Wallboard
2	0	0	0
4	0	0	0
6	0.1	0	0
8	0.2	4.5	0.6
10	0	13.2	0.4
12	0.2	0.7	1.7
14	0.7	-	1.0
15	1.4	-	-
16	0.4	-	-

(Because of different sampling times, some of the above values were interpolated for comparison and used in this report.)

More recent tests performed by the Forest Products Laboratory are reported by Schaffer and Eickner[307] and reflect the results of three experimental fires conducted in a corridor with three different wall linings (see Table 5).

TABLE 5. ANALYSIS OF THE ATMOSPHERE IN A BURNING CORRIDOR

Time, min	% CO by Volume		
	Test 1 - White Pine Wainscot up to 3 ft, Flat Painted Plaster Walls Above	Test 2 - Prefinished Wood-Grained Hardboard on Walls	Test 3 - Red Oak on Walls
1:30	-	-	0.1
3:15	-	0.15	-
4:40	-	-	0.5
6:15	0.3	-	-
6:30	-	4.5	-
8:15	-	7.0	-
10:00	-	10.0+	-
13:00	0.3	-	-

(3)   <u>Broido and McMasters</u>[37]

A number of experimental building fires has been reported by Broido and McMasters, and these are summarized as follows:

<u>Richmond Test No. 1</u> - A two-story, four-apartment building measuring 50 ft × 28 ft, with stucco exterior, sheetrock interior, oak floors, and scrap lumber simulated furnishings (see Table 6).

TABLE 6.   ANALYSIS OF GAS SAMPLES

Time, min	% CO by Volume
13	0.1
19	0.1
34	4.0
44	8.0
113	0.1
197	0.1

<u>Richmond Test No. 2</u> - This test was conducted on a single-story wood house measuring 50 ft × 22 feet. Carbon monoxide levels reached a momentary (1 or 2 min) high of 1.0 percent during the test at 35 min and immediately fell to its previously apparent level of less than 0.2 percent.

<u>Los Angeles Test No. 1</u> - This test was conducted using 2 × 4 mill ends scattered to a depth of about 2 ft in a single room of an abandoned school. Carbon monoxide levels rose gradually to a high of 0.5 percent at the end of the 17-min test. This fire was extinguished before fuel became involved at floor level.

<u>Los Angeles Test No. 2</u> - A single room of an abandoned school was loaded with lath and pallets and allowed to burn for less than 12 min before manually extinguished. Carbon monoxide levels began to rise rapidly at 4 min and went off the 2-percent scale at 6 minutes.

<u>Briones Burn</u> - Windrows of trees and brush were burned over an 11-acre plot, and carbon monoxide

concentrations were recorded 3 ft inside the edge and 5 ft outside the edge of one of the windrows. At a point 3 ft inside the windrow, levels greater than 2 percent at 3 min caused failure of the detection equipment. At a point 5 ft outside the windrow, levels above 2 percent were recorded for a brief 5-min period after which levels dropped to less than 0.1 percent for the remainder of the burn.

Camp Parks Burn - Approximately 250 tons of scrap lumber and poles were distributed in piles measuring 20 ft × 15 ft, 7 ft high and spaced over a 4-acre plot. Gases were sampled in a rubble fire wood pile, a pile containing rubble, and midway between two piles. A shelter within the burn area was also monitored. Concentrations recorded in the rubble pile rose to 5 percent or higher (7 percent) for approximately 3 hr and only fell back to 0.04 percent when the rubble pile fell below the intake level of the vent. Carbon monoxide levels recorded in the rubble fire pile rose to 1.5 percent at 6 min and then fell to levels of 0.11 percent at 18 min and 0.16 percent at 33 minutes.

(4)   St. Lawrence Burns[311]

Six abandoned dwellings, three with combustible linings and three with relatively noncombustible linings, were burned with wood cribs as simulated furnishings. The instrumentation used was not capable of measuring beyond 1.5-percent carbon monoxide; however, these maximums were recorded as early as 2-1/2 min in structures lined with combustibles. Levels of 1.1 percent were recorded at 5 min in structures with relatively noncombustible linings.

b.   Carbon Monoxide Monitored Outside of Burning Structures or at Relatively Greater Distances from the Burning Fuel

(1)   U. S. Forest Service Burns[82, 274]

These burns have been conducted on a larger and more fully instrumented scale than any others to date.

One such fire, designated as Plot 760-2, covered 4-1/2 acres and contained thirty-six piles of 20 tons each of pinion pine and juniper, each pile 47 ft square and 7 to 10 ft high. Carbon monoxide concentrations were measured at a 20-ft height over one of the central piles and measured a level of approximately 1 percent for a period of 9 min, gradually dropping to 0.5 percent over the next 16 minutes.

Concentrations in two other plots are also reported. In test fire 380-2-63, levels of carbon monoxide as measured 12 in. above the ground exceeded 2 percent for approximately 5 min and then fell to a level below 0.5 percent for the remainder of the test. In test fire 760-1-64, levels measured at a height of 20 ft never rose above 0.2 percent.

(2)   Camp Parks Burn[37]

In this burn, carbon monoxide was monitored at a point between two burning piles approximately 9 ft from each one. The reported carbon monoxide levels never exceeded 0.08 percent.

c.   Summary

Experimental work to date indicates that extremely high (relative to toxicity values) levels of carbon monoxide may be formed in the immediate area of burning material. However, these high concentrations last only for a short period of time. In open fires, the maximum carbon monoxide levels and the time span during which the levels are above any particular concentration both decrease rapidly with increasing distance from the burning fuel. In open fires, the highest level recorded at horizontal distances of 9 ft or greater has been 0.08 percent.

In closed fires, the levels are higher and last longer. No specific values can be attached to the levels of carbon monoxide to be expected; however, it has been shown that levels well above the survivable limits have been recorded in the enclosed experimental fires.

As a part of analyzing the important parameters in a fire, a variety of interior finish building materials was monitored for their production of combustion products during the standard ASTM E-84 tunnel test. This test and the method of gas analysis used is fully explained in Section VII. Approximately 150 materials were burned and the gases analyzed for their carbon monoxide content. In addition to the momentary maximums produced, the total production of carbon monoxide during the carefully controlled test was also monitored. The results indicate an extremely wide variance, with some materials producing as much as 6, 7, 8, and 16 percent carbon monoxide in the combustion product stream. These results indicate the high concentrations of carbon monoxide that might exist within a structure where there is a fire.

In terms of the mass fire life hazard, these results indicate the importance of protecting against the influx of fire gases in those areas where shelters are within a building and close to combustibles. To date, the existence of a serious hazard of carbon monoxide in the open has not been shown either theoretically or experimentally.

5.   Anoxia as a Factor

Oxygen is necessary for the process of combustion, and, as such, it is consumed in the process. Several experimenters have monitored the atmosphere in and around test fires in order to determine the oxygen content of that atmosphere.

Tests performed by the Forest Products Laboratory and reported by Bruce[46] show oxygen concentrations in one fire reduced to 0.8 percent and below 10 percent for approximately 5 minutes. In two other fires, the oxygen content never fell below 12 percent. More recent work by the Forest Products Laboratory reported by Schaffer and Eickner[307] reflects a reduction of oxygen in one test to 4.4 percent.

Work by Kingman, et al.[169], as reported earlier in Table 3, shows reduction of oxygen in one test to 0.2 percent and in the other to 0.3 percent. No complete time factor is given.

In a series of tests reported by Broido and McMasters[37], oxygen concentrations within burning buildings reached a low of 5 percent and stayed below 10 percent for a period of approximately 10 min in one test. In another test, the levels reached a low of less than 2 percent and stayed below 10 percent for a period of approximately 10 minutes. Oxygen concentrations measured 9 ft from the nearest fuel in the center of a large burn did not fall below 20 percent, while, during the same burn, concentrations measured inside a burning fuel-rubble pile fell below 2 percent for a short period and stayed below 10 percent for nearly 4 hr until the rubble fell below the intake level of the sampling vent.

Countryman[82] has indicated the oxygen drop recorded in two test fires. The lowest level reached was 5 percent (below 10 percent for approximately 5 min) in test fire 380-3-63. In the other, test fire 760-1-64, levels never dropped below 14 percent.

During the St. Lawrence Burns[311], the oxygen concentrations were reduced to levels of 6.5, 6.0, 9.4, 6.6, 8.9, and 2.7 percent. Unfortunately, no time durations were recorded.

In summary, experimental work to date has shown that oxygen concentrations in and immediately around burning structures can drop to levels very near zero; however, these levels have remained low only for short periods of time. In addition, these low levels could not be found at distances of 5 ft, 9 ft, and 25 ft from burning fuel. Oxygen within smoldering rubble piles has been shown to drop below 2 percent and stay below 10 percent for 4 hours. Tests conducted by SwRI indicate that oxygen concentrations in the combustion stream, during the burning of interior finish building materials, can easily drop to near zero for periods of 5 min or longer. Some materials

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were found to drop the oxygen levels to as low as 2 percent. Oxygen levels, therefore, are a serious matter for persons caught in a burning building, but they do not appear to be a factor for those caught in the open.

6. Other Toxic Gases

The pyrolysis of materials in a mass fire can be expected to release a wide range of gases ranging from irritants to anesthetics, to nerve gases, and others of a highly toxic nature.[385] Table 7 is presented only to illustrate the complexity of combustion gases. This table should be viewed with care as all the materials were not burned under the same conditions.[76]

A survey conducted by Underwriters' Laboratories[95] bears witness to the complexity of defining the toxic gases produced from certain building materials. The toxic gas concentrations reported by the many authors who have investigated this problem were measured at or very near the burning fuel, and, as a result, extrapolation to the mass fire environment is at least very difficult if at all possible. Review of the literature and reports available indicate that no theoretical or experimental work has been accomplished in defining the toxic gases to be expected in a mass fire environment.

Easton reports that in some cases the major injuries resulting from the inhalation of smoke may be caused by toxic constituents other than carbon monoxide. He lists these various constituents as: carbon dioxide, methane, acetic acid, formic acid, methyl alcohol, tar, and other products simply referred to as including hydrogen, acetone, formaldehyde, hydrocarbons, organic acids, alcohols, aldehydes, esters, ketones, and phenol derivatives.[99, 100]

Table 8 (shown on page 33) as prepared by Martin presents the main volatile products produced from the low-rate pyrolysis of cellulosic materials in relation to temperature.

The NFPA Fire Gas Research Report[243] points up the presence and toxicity of nitrogen oxides in a fire, plus chlorine, sulfur dioxide, cyanides, and carbon disulfide. No experimental data are presented.

In 1953, Bruce reported on experimental work conducted by the Forest Products Laboratories[46] in which the concentration of unsaturated hydrocarbons, saturated hydrocarbons (calculated as methane), and hydrogen were monitored. In 1959, Coleman presented a review of the published results of work on the problem of gaseous combustion products from plastics.

The results of these investigations point up the many toxic gases to be found in the combustion products produced by burning various materials. Any attempt to draw conclusions from this work as regards the mass fire environment would simply be conjecture. The problem of toxic gases has

TABLE 7. SUMMARY OF DECOMPOSITION PRODUC

Investigator	Material	Method of Testing	Oxygen (O_2)	Carbon Dioxide (CO_2)	Carbon Monoxide (CO)	Chlorine (Cl_2)
F. D. Snell	Melamine resin, paper, or wool	Heated in a current of air and products passed over rats in cages	Not analysed			
J. C. Olsen	Wood	5 lb burned in 110 ft^3 air	9.8	6.2	6.2	-
	Rubber	Insulation on cable in 5-liter flask	6.6-13.4	6.6-13.6	3.4-7.6	-
	Wool	Heated in silica tube with a current of air	6.6-14.2	4.6-9.2	0.5-5.0	-
	Silk		4.0-8.0	8.0-12.6	3.0-4.4	-
F. E. T. Kingman, et al.	Timber and fibre insulating board	Burning house	19.9	0.7	0.3	-
			1.6	17.8	19.8	-
			0.3	9.2	16.7	-
E. H. Coleman and C. H. Thomas	Chlorinated methacrylate resin 27% chlorine	0.5 g at 550°C in 5 liters air	n.d.	2.6	2.2	0.0
	Polyvinyl chloride 57% chlorine	0.25 g at 550°C in 5 liters air	n.d.	2.1	1.1	0.0
	Polyvinyl chloride fabric	0.5 g at 550°C in 5 liters air	n.d.	2.0	0.4	n.d.
A. Schriesheim	Plywood	Heated at 550°C in 5 liters air	2.8	17.1	3.6	-
	Plywood P.V.C. and flame-retardant paint	Heated at 550°C in 5 liters air	2.1	17.1	5.1	-
	Plywood with polyester resin and flame-retardant paint	Heated at 550°C in 5 liters air	2.6	14.7	13.2	-
	P.V.C. coating only	Heated at 550°C in 5 liters air	0.3	10.1	5.8	-
	Vinylidene coating only	Heated at 550°C in 5 liters air	17.0	0.4	-	-
H. A. Watson	Foamed polyvinyl chloride	2-3 g heated electrically, in 270 liters air	20.7	0.16-0.35	0.023-0.040	0.0
	Foamed acrylonitrile		19.3	1.26-1.31	0.041	0.0
L. B. Berger	Phenolic resin with fillers	As above	n.d.	n.d.	0.017-0.046	-
	Melamine resin with fillers		n.d	n.d.	0.012-0.075	-

Source: See Ref. (76)

Analyses (% volume)

Chlorine (Cl$_2$)	Hydrogen Chloride (HCl)	Carbonyl Chloride (COCl$_2$)	Hydrogen Cyanide (HCN)	Ammonia (NH$_3$)	Hydrogen Sulphide (H$_2$S)	Nitrous Fumes as NO$_2$	Notes
							Demonstration that shows toxicity was due to carbon monoxide and not hydrogen cyanide.
	-	-	-	-	-	-	
	-	-	-	-	0.1	-	10% of hydrocarbons.
	-	-	1.3-2.5	1.3-2.6	0.02-0.40	-	
	-	-	2.2-6.8	3.1-3.6	-	-	
	-	-	-	-	-	-	3 min from start.
	-	-	-	-	-	-	1.9% hydrogen 12 min from start
	-	-	-	-	-	-	47% hydrogen 18 min from start.
0	0.6	0.0005	-	-	-	-	
0	1.8	0.0005	-	-	-	-	
	2.9	n.d.	-	-	-	-	
	-	-	-	-	-	-	3.4% hydrocarbons.
	3.1	-	-	-	-	-	
0	3.8	-	-	-	-	-	
	4.7	-	-	-	-	-	
	1.1	-	-	-	-	-	
0.0	0.005-0.023	0.0	0.001-0.003	0.002-0.003	-	0.001-0.002	Tests made to examine effects of blowing agents
	0.002	0.0	0.002	0.002	-	0.002	
	-	-	0.0-0.003	0.002-0.110	-	-	Carbon monoxide was highest with fillers such as wood meal and cotton
	-	-	0.002-0.25	0.006-0.180	-	-	

TABLE 8.   LOW-RATE PYROLYSIS OF CELLULOSIC MATERIALS

Temperature, °C	Process	Main Volatile Products
<200 (<392° F)	Dehydration	Water vapor
200 to 280 (392° to 536° F)	Endothermic "dry" pyrolysis	Carbon dioxide, water vapor and acetic acid
280 to 500 (536° to 932° F)	Endothermic pyrolysis to char	Carbon monoxide, hydrogen, methane, carbon dioxide, acetic acid, formic acid, ethanol, acetaldehyde, acetone, diacetyl, methylethyl ketone, ethylacetate and tars
>500 (>932° F)	Gasification and char	Hydrogen and carbon monoxide

Source: See Reference 200

long been recognized; however, the work to date has been very limited and narrow in scope.

The only general conclusion that may be drawn is the possibility of significant quantities of particular gases in those areas where large amounts of a particular combustible may be burning.   For example, the burning of a large rubber warehouse might produce large quantities of hydrogen sulfide and sulfur dioxide; a burning wool mill might produce hydrogen cyanide; and a plant producing chlorinated products might produce chlorine gases while burning.   But here again, there is no evidence to indicate that these gases would be sufficiently concentrated over an area in the open to constitute a life hazard.

7.   Smoke Production

In addition to the presence of carbon monoxide, carbon dioxide, heat, high winds and an endless variety of toxic gases, there will be smoke which is a factor that must be considered.   Smoke is here defined as any solid particulate matter in the air as opposed to gases or vapors that may also be present.   Review of the work accomplished to date on smoke indicates that the effort has been extended primarily in defining the density of smoke as it applies to visual obscuration within buildings.   This has been accomplished to date by two methods.   The first method measures the degree of light absorbed between a light source and receiver (photocell) and reports the results as percentage of light reduction or absorption.

$$S_x = 100(1 - I_x/I_o) \qquad (2)$$

where

S_x = light obscuration expressed as a percentage

I_o = incident light intensity

I_x = transmitted light after passing through a path length x

The quantities I_o and I_x are measured directly by the smoke meter, and, hence, the percentage obscuration for a given thickness of smoke may be measured. This method is not directly proportional to the thickness of the smoke zone.

The second method which measures optical density and is directly proportional to the thickness of the smoke zone is expressed as

$$D_x = \log_{10} I_o/I_x \qquad (3)$$

where

D_x = optical density of the smoke

thus

$$D_x = \log_{10} \left[\frac{100}{100 - S_x} \right] \qquad (4)$$

From this definition of optical density, it may be deduced that for a uniform medium of path length, nx,

$$D_{nx} = n \log_{10} I_o/I_x = n D_x \qquad (5)$$

the optical density is directly proportional to the path traversed by the light, and the value for any path length can readily be obtained from the optical density per unit path.[313]

Tests conducted by the Division of Building Research, National Research Council of Canada[311] showed that visibility on the second floor of a building which was ignited on the first floor was reduced to 4 ft within 1.5 to 2.4 min in an open room and within 3.4 to 5.7 min in a closed room. Visibility in the basement was not reduced to the 4-ft criteria until 10.7 to 17.6 minutes. The 4-ft visibility here means the distance at which the holder of a fireman's hand lamp can perceive objects by the light they reflect.

In tests conducted by Kingman, et al.[169], the smoke concentrations measured reduced light transmission 95 percent within 6 to 8 min in

one test and 10 to 24 min in another. In tests reported by Schaffer and Eickner[307], transmission was reduced 95 percent within 4 to 6 minutes.

A survey by Yuill and Bieberdorf[385] revealed the different methods used by the Fire Research Organization in England, the Los Angeles Fire Department, and Underwriters' Laboratories. In addition, the National Bureau of Standards is presently working on development of a method.[131]

The one single method which has seen the most use is that used in conjunction with the ASTM E-84 tunnel test. Results from this test are related to the smoke output from red oak flooring and asbestos-cement board as 100 and zero, respectively. Results indicate the ability of many materials to produce copious quantities of dense smoke within seconds and yet others show up quite smoke free.

In summary, smoke is perhaps the least defined aspect of mass fires. This is not to say that there has been a lack of interest in smoke; on the contrary, there has been considerable interest. However, most of it has been directed toward measurement of the light obscuration. A recent report by Underwriters' Laboratories[32] and development of still another method of smoke measurement (light obscuration) by the National Bureau of Standards[131] is evidence of this continuing interest. Papers on these and other aspects of the smoke problem were presented at a symposium on smoke held during the ASTM Annual Meeting in June 1966.

Other factors such as the psychological fear, the panic and the health hazard created by smoke have been well recognized. However, review of the literature indicates that little if any definitive work has been done regarding the hazards of smoke as an asphyxiant, irritant, lachrymator, or possible cause of chemical tracheitis.

8. Winds and Firewhirls

Wind has undoubtedly been recognized as a strong factor in the initial buildup, rate of burning, and spread of fires.[375] It plays a major role in the spread of wildland fires and influences the spread of urban fires as well. It has the ability to supply fresh air and quantities of oxygen to a fire and can drive the fire toward fresh fuel. Wind also aids in the spreading of fire by carrying firebrands far ahead of the main burning area. One investigator has associated wind speed profiles with fire behavior and developed an equation rating strength of the wind field and energy release of a fire to the development of convection columns.[68]

Review of the literature on past fires relates many subjective accounts of high winds encountered within and immediately around large fires. Winds of 70 mph were reported in Darmstadt[354] during a mass fire. In Tokyo during the 10 March 1945 firestorm, winds are reported to have risen from 25 mph to 70 mph.[355] At a distance of 1.5 miles from Hamburg and 4 miles from the core area of the firestorm, winds increased from 11.2 to 33.6 mph.[101]

At the main fire station in Hamburg, which was located 0.3 miles from the edge of the firestorm, it was reported to have taken ten men to force open a garage gate against the violent windstorm.[101]

Wind speeds within the Tokyo fire of 1923 were estimated in excess of 150 mph.[59] During the forest fire in 1910 which burned over 3,000,000 acres in northeastern Washington, northern Idaho and western Montana, the speed of the wind and fire are noted as having reached 70 mph.[320]

In any discussion of winds within a mass fire area, firewhirls must be considered. It is possible that many of the subjective accounts given may be a result of local whirlwind conditions. The report of 150-mph winds in the Tokyo fire of 1923 certainly appears to be such a report. There is frequent reference in Busch's account of a tornado like wind which speaks strongly of a firewhirl.[59] Hans Brunswig of the Hamburg Fire Department reported that winds of 112 mph occurred in the narrow canyons of the streets and that wind velocities resembled those found in a hurricane without showing the typical cyclonic behavior.[101] The U. S. Strategic Bombing Survey reports that for an unspecified time winds in Hamburg "....prior to attacks were never over 2 or 3 mph, which is practically still air."[351] However, during the fire, the inrushing air was reported to have reached gale proportions.[352]

Simulated mass fires conducted by the U. S. Forest Service have been instrumented to indicate the internal wind velocities. The highest recorded to date was 52 mph in test fire 760-2 (a 5-acre burn), and this wind speed was recorded until the sensor failed.[274] During this same fire, wind speed, measured at a distance of 100 ft from the edge increased from 2 mph to 8 mph (at the 20-ft elevation) at 12 min and then settled to approximately 6 mph for the next 48 minutes. In test fire 460-14 (a 40-acre burn), the wind speed measured 100 ft from the edge increased from 3 mph to 12 mph (at the 20-ft elevation) at 12 min and then settled to 9 to 10 mph for the next 48 minutes.[274] Several firewhirls occurred during and immediately following this fire and are described by Evans and Tracy.[106] These firewhirls were seen for several hours following the fire. Photos of two firewhirls were taken and are shown in Figure 5.

In a study of large urban conflagrations by Chandler, et al.[68], wind speeds at various times during the mass fires are reported. The highest wind speed of 38 mph is reported in Bandon, Oregon, and this is clearly due to the natural wind speed and not the fire. Wind speeds during the San Francisco fire of 1906 are reported as varying from 20 mph to a low of 5 mph and then back up to 26 mph. Wind speeds during the Great Chicago Fire are reported as varying from 4 to 7 mph; however, other accounts describe the wind speeds as a "gale" and offer descriptions of its violence and the difficulty in walking.[214]

In addition to these accounts which may be difficult to ascribe to a particular phenomenon surrounding a large fire, there are many accounts
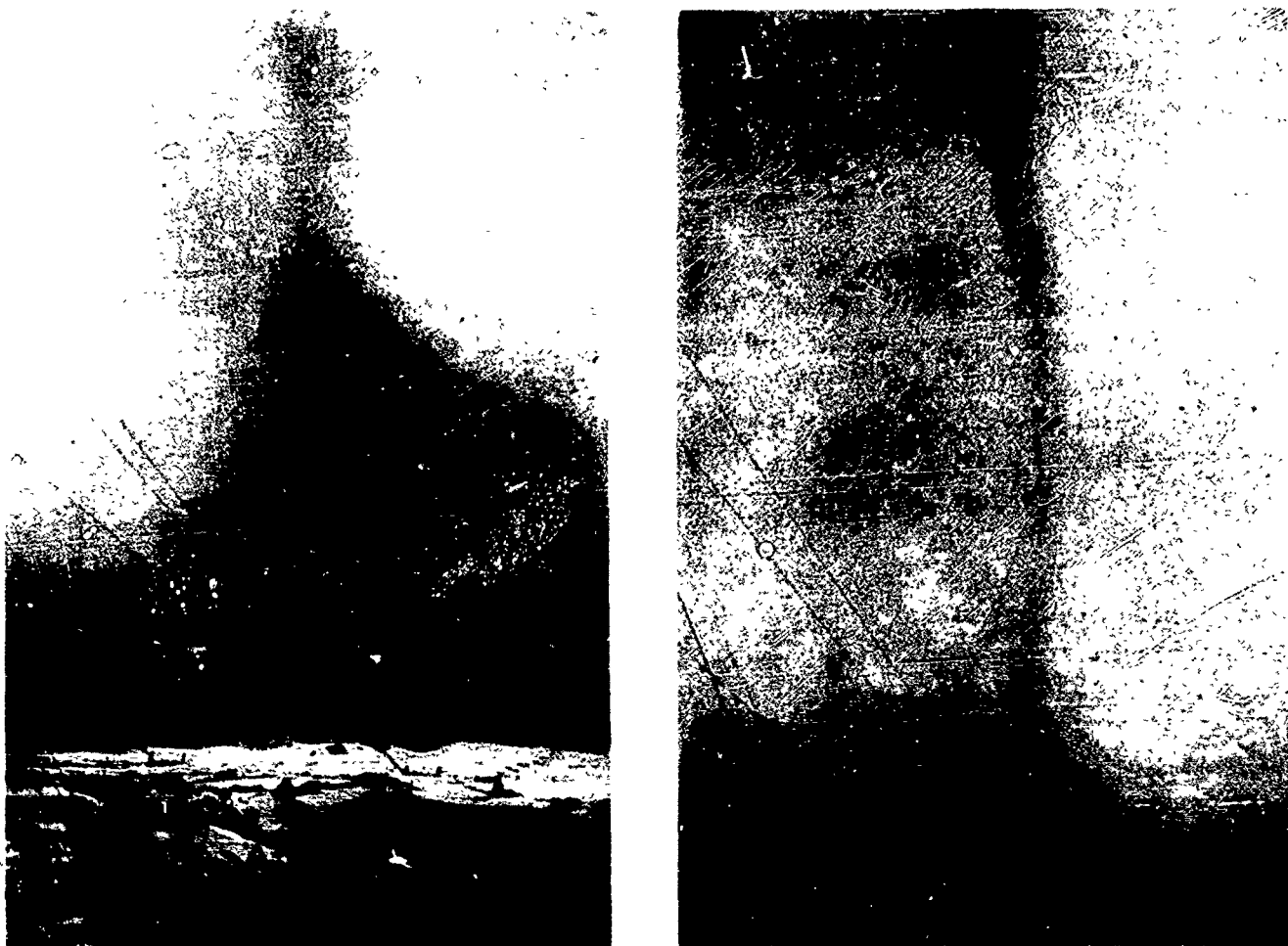
Source: SwRI

FIGURE 5.   FIREWHIRLS DURING U. S. FOREST SERVICE
EXPERIMENTAL BURN 460-14

which are clearly labeled as firewhirls. Hissong reports that hundreds of firewhirls occurred during an oil fire in California in 1926[153] which covered 900 acres. One firewhirl picked up a cottage and carried it 150 ft before dropping it in a field. Byram[61-64] concluded that some firewhirls appeared to cover an area of about 10 acres. Graham reports on witnessing a firewhirl that twisted and broke off a Douglas fir tree (40 in. in diameter at breast height) at a point 20 ft above the ground.[127] In another report[128], he describes twenty-eight whirlwinds that occurred in the Pacific Northwest. Some of these whirls are cited as having a diameter of 1200 ft and a height of 4000 feet. The intensity of firewhirls is stated as varying "from that of a dust devil to a whirlwind that pitches logs about and snaps off large trees. Velocities in the vortex are extremely high, and, as in other forms of whirlwinds, the greatest speed occurs near the center." Byram and Martin report that, "These whirls, or 'fire devils' as they are sometimes called, range in size from small twisters a foot or two in diameter up to violent whirls equal to small tornadoes in size and intensity."[64] Laboratory studies on firewhirls at the Southern Forest Fire Laboratory in Macon, Georgia, indicate that there "...is a sudden threefold increase" in the burning rate of the fuel used in the firewhirl experiment as the firewhirl occurs.

Countryman[82] reports that firewhirls up to a quarter of a mile in diameter have been observed and that a large firewhirl that developed in a fire near Santa Barbara, California, in 1964 moved out of the fire area, demolished a house, severely damaged several others, stripped limbs from and uprooted several large trees.

In summary, winds encountered within and immediately around a mass fire vary considerably; however, it has been demonstrated that high winds, 52 mph or greater, do occur within fire areas and that the velocities encountered are related to the intensity and area of the fire. The 52-mph or greater wind was recorded in an experimental burn 5 acres in size. This indicates the potential that larger more intense fires may have for the development of winds (including firewhirls).

Theoretical investigations of winds in a firestorm by Nielsen have estimated winds of approximately 35 mph assuming the average ground temperature to be 425°C (800°F).[251]

Winds during the large firestorms in Germany during World War II are reported as high as 70 and 112 mph; however, it is not clear as to whether these velocities occurred locally as firewhirls or whether they were present over the entire fire area, fully around 360 degrees of the perimeter.

IV. SURVIVAL CRITERIA

A. General

The environment within a mass fire poses a threat to life safety since conditions may occur which are beyond the limits of man's physiological endurance. Man is sensitive to heat both internally and externally; he is also sensitive to the makeup of the air or gases that he breathes. Thus, evaluation of the hazard of the mass fire environment must be in terms of man's ability to survive in that environment. The previous chapter provides a description of the environment within a mass fire. This chapter outlines man's physiological limits in terms of the specific variables found within a mass fire.

These variables are discussed in terms of survival criteria and include heat, anoxia, carbon monoxide, carbon dioxide, and other gases. These variables may be directly contributed by the fire or they may be only remotely associated with it. For instance, people in an underground shelter protected from the direct results of an overhead fire may produce a hazardous environment within the shelter by means of their own body heat, the carbon dioxide they produce, and their consumption of oxygen.

B. Heat

Man's reaction under elevated temperatures has perhaps been studied more than any other variable that may constitute a life-safety hazard in the mass fire. Heat may present itself in a number of ways and at different rates. Experimenters over the years have studied heat in its many forms and at different rates. There is, generally speaking, surprisingly close agreement on the tolerance limits of man.

One of the earliest experimental efforts in an attempt to identify man's tolerance to high levels of heat is reported by Tillet[337] who in 1764 observed people entering large baking ovens in which the temperature exceeded 100°C (212°F). Later investigations indicated their voluntary exposure to temperatures of 112° to 120°C (230° to 248°F) for periods of 15 to 20 min and to temperatures of 140°C (284°F) for 5 minutes.

Buettner[52-56], Webb[367], and Hardy[141] have studied man's tolerance to extreme heat and defined the three principal modes of heat transfer to man as:

(1) heat transfer by means of hot air - convection;

(2) contact with hot objects - conduction; and

(3) radiation from hot surfaces and gases.

Hardy presents the general equation of heat transfer as the algebraic sum of the factors involved[141]

$$H_L = H_R + H_C + H_D + H_V \tag{6}$$

in which

H_L is heat loss or gain

H_R is radiant heat loss

H_C is convective heat loss

H_D is conductive heat loss

H_V is evaporative heat loss

and states that the quantities may be positive or negative depending upon the direction of heat flow. Generally, they are considered to be positive when the transfer of heat is from the body surface into the environment. Man must live in thermal equilibrium with his environment except for short-term transient adjustments which must be made.

The heat balance equation can be stated as:

$$H_p - H_L = S \tag{7}$$

in which

H_p is heat production within the body

S is body heat storage (positive when body is gaining heat)

Within certain limits, the human body can compensate for heat received in any of the three ways. Blood circulation and sweat loss are important factors in preventing physiologic damage. Buettner cites radiation of more than 0.06 cal/cm^2-sec; hot, calm air of 300°C (572°F); and air in motion at more than 100°C (212°F) as producing skin burns so rapidly that the body is unable to protect itself[52-56]. Below these limits, the body's ability to compensate and protect itself is obviously related to the duration of exposure and the rate at which the intensity of heat increases.

1.   Convective Heat

Buettner estimated that, in calm air at a temperature of 50°C (122°F), the escape time from a heated, enclosed space is several hours; at 70°C (158°F), it is 1 hour; at 130°C (265°F), it is 15 min; and at 200°C to 250°C (400° to 500°F), it is less than 5 minutes. Escape time here is defined

as the minimum time required for collapse to occur. He presents an interesting chart showing safe exposure times at various temperatures (see Fig. 6).
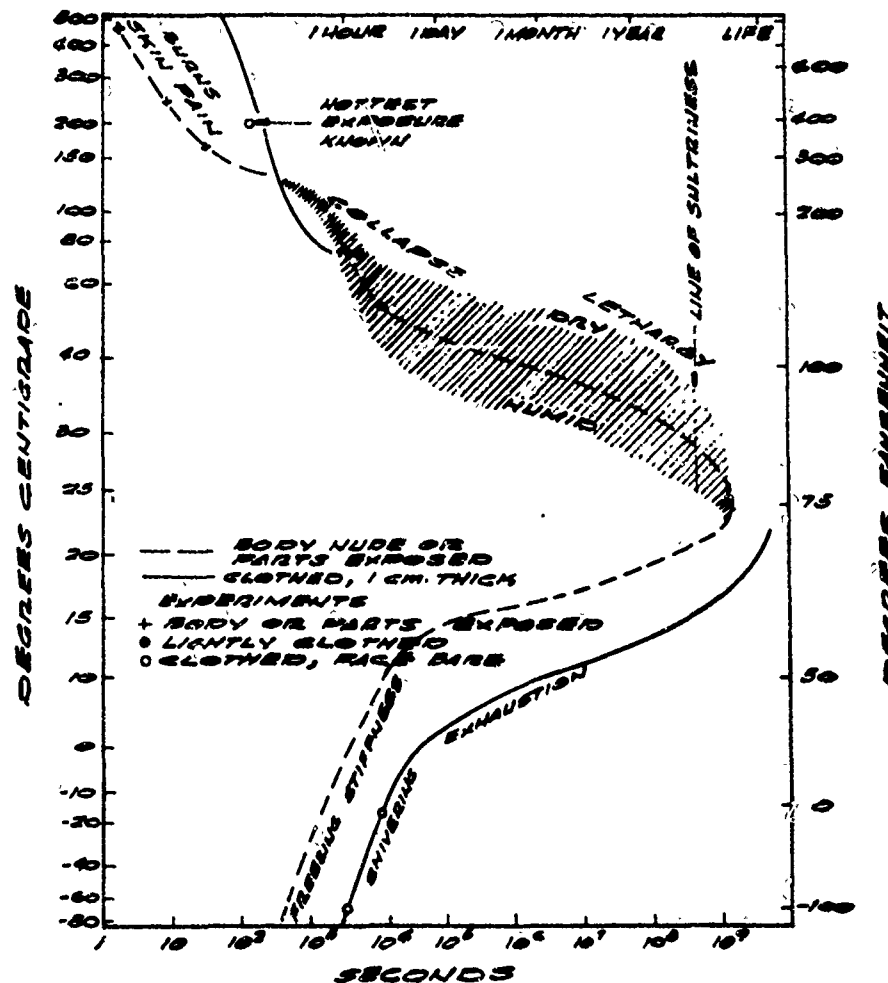
Source: See Ref. (57.)

FIGURE 6. SAFE EXPOSURE TIME FOR MAN IN
EXTREME THERMAL ENVIRONMENT

Heat may be encountered both inside and outside of shelters. The external heat which results from the fire generally will be a dry heat, relatively low in humidity[85]. The heat generated within shelters by the occupants will raise the humidity of the interior. From experimental evidence, no specific effect of humidity has been determined. In its influence on the observed physiology of the body and on body tolerance, an increase in humidity is equivalent to a definite increase in temperature[26].

Experimental work by Blockley and Taylor[25] show the mean value of tolerance times (see Table 9) for two subjects in exposures of 82°C (180°F) and above at low humidity.

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TABLE 9. TOLERANCE TIMES FOR TEMPERATURES

Ambient Temperature Level	Mean Tolerance Time for Four Exposures, min
82°C (180°F)	49
93°C (200°F)	33
105°C (220°F)	26
115°C (240°F)	23.5

These temperature-tolerance times are in agreement with Figure 6. Initial distress, as noted by the subjects in the experiments, was observed at shorter times. At 82°C (180°F), initial distress first occurred in the most sensitive subject approximately 7 min prior to the mean tolerance time. At 115°C (240°F), this initial distress occurred approximately 25 min prior to the mean tolerance time. For the average shelter population in a mass fire environment, the line of initial distress may be of more interest than the mean tolerance time. The mean tolerance time is much closer to the collapse and incapacitating state for the average individual and may even be beyond that state for some, i.e., the aged and sick.

Experimental work conducted by Moritz, Henriques, et al.[229, 230, 232], confirmed the work of previous investigators in regards to the direct skin temperature and cutaneous burning. Buettner cited the skin temperature at the "pain threshold" to be between 42° and 46°C (108° and 115°F), and the pain temperature to be 51°C (124°F). He stated that burns will occur whenever the skin of the epidermis exceeds 54°C (129°F)[52-56]. The average skin temperature is 33°C (91°F). Moritz and coworkers found that, when the temperature of the skin is maintained at 44°C (111°F), the rate of injurious change exceeds that of recovery by so narrow a margin that an exposure of approximately 6 hr is required before irreversible damage is sustained. At surface temperatures of 70°C (158°F) and higher, the rate of injury so far exceeds that of recovery that less than 1 sec is required to cause irreversible injury[230]. These conclusions were drawn as a result of experimental work with both porcine (pig) and human skin. The results of this work indicated that at similar skin surface temperatures there is little or no quantitative difference in the susceptibility of human and porcine epidermis to thermal injury. The relative vulnerability is shown in Figure 7.

As a result of the work at these temperatures, the authors concluded that conduction of the heat energy away from the skin surface by way of the blood stream does not afford a significant degree of protection against epidermal injury.
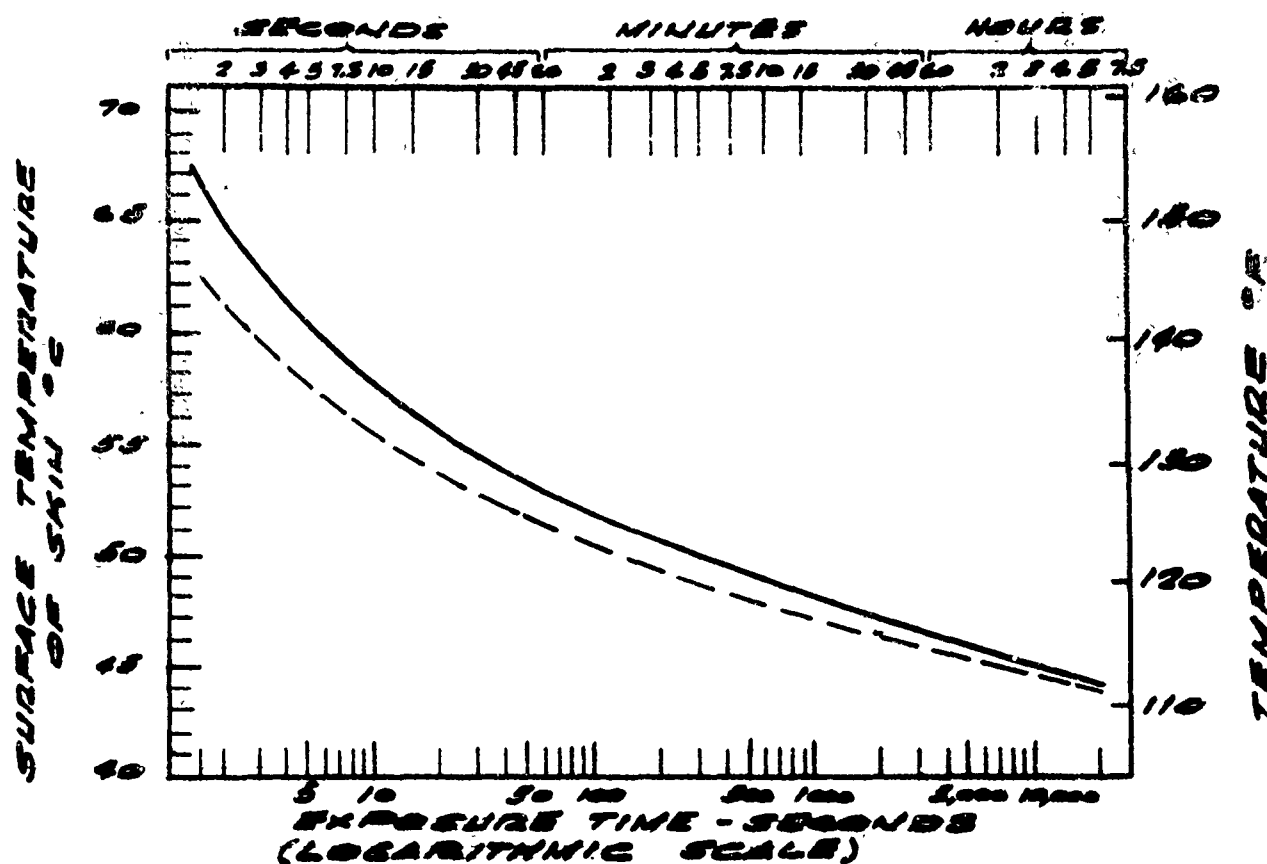
Source: See Ref. (230)

FIGURE 7. RELATIVE VULNERABILITY OF PORCINE AND
HUMAN SKIN TO THERMAL INJURY

Moritz, et al.[232], conducted an experimental study of the
casualty producing attributes of conflagrations. Goats and dogs were exposed
to excessive convective and radiant heat of varying duration and intensity.
The results of these experiments indicated that there are two types of hyper-
thermic circulatory failure, one central and the other peripheral. The former
occurred in some animals as the result of brief exposures at high [>200°C
(>392°F)] circumambient temperatures, whereas the latter occurred after
long exposures at lower temperatures. It was evident that large animals
exposed to conflagration heat may receive injuries that are almost immediately
fatal and that are not necessarily contributed to by asphyxia, carbon monoxide
poisoning, or the inhalation of flame or fumes. It was apparent that almost
immediate death may result from systemic disturbances caused by the heat
flowing through the surface of the body. The moderate to severe pulmonary
edema that was observed in dogs and goats bore no relation to the inhalation
of heat but was a result of circulatory failure incident to systemic hyper-
thermia[232].

Some temperatures of approximately 90°C (196°F) could be
tolerated for 45 min without burning, whereas, at 100°C (212°F), burning

occurred in 12 min, and, at 180°C (357°F), the longest exposure that could be tolerated without irreversible cutaneous injury was 30 seconds. At relatively low temperatures of heated air [under 120°C (248°F)], man, because of his ability to sweat, is undoubtedly less susceptible to injury than the pig. It is doubtful, however, that sweating provides a significant degree of protection at temperatures over 120°C (248°F), because, at such levels, the rate at which heat is transferred to the skin is considerably more rapid than the rate at which it can be dissipated by vaporization of sweat[232].

The severity of the physiologic disturbances that result when animals are exposed to excessive heat are frequently disproportionate to that of the cutaneous burning. Rapidly fatal systematic hyperthermia may result from long duration exposures at temperatures insufficient to cause cutaneous burning. Higher intensity exposures may cause extensive and severe cutaneous burning and yet be of too short duration to cause a significant rise in body temperature.

The severity of the immediate physiologic disturbances resulting from exposure to excessive heat appears to bear a direct relationship to the extent to which the body temperature is increased. Exposures that generally cause the rectal temperature to rise above 42°C (108°F) and those that invariably caused it to rise as high as 44°C (111°F) resulted in rapidly fatal circulatory failure.[232]

As a result of this work, Moritz, et al., concluded that there is no reason to believe that man and pig differ greatly in respect to the rate at which heat is transferred from the skin to the interior of the body. Thus, man's susceptibility to development of rapidly fatal hyperthermia when exposed to environmental temperatures in excess of 120°C (248°F) is probably similar to that of the pig.

Moritz, et al., observed that cutaneous hyperthermia was capable of causing the plasma potassium to rise as much as 17 milliequivalents per liter and suggested acute potassium poisoning as a potential cause of death. There appeared to be a definite correlation between survival and the height to which the internal body temperature was raised.

Other experiments performed by McLean, Moritz and Roos[217] established that severe and extensive cutaneous burning may result in a rapid rise in plasma potassium to levels ordinarily considered incompatible with life. Such levels are attained when a large proportion of the body surface of an animal whose red blood cells normally have a high potassium content is maintained at 95°C (167°F) for more than a few minutes. That lower surface temperatures may also be responsible for fatal hyperpotassemia is suggested by the fact that potassium may be released rapidly from blood cells in vitro at temperatures of 60°C (140°F). Because of the slowness with which potassium is released at lower temperatures and the rapidity with which excess potassium leaves the blood stream, it is not likely that thermal exposures of insufficient intensity to cause severe cutaneous burning could

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cause sufficient damage to the erythrocytes to produce dangerously high plasma levels.

The cause of death from heat in those cases where the flow of potassium is low enough to allow the blood stream to release the potassium was determined by Moritz, et al., to be systemic hyperthermia. This systemic hyperthermia, which is caused by conduction of heat to the interior of the body by way of the blood stream, leads to a rapid and progressive decline in blood pressure and failure of circulation due principally to peripheral vascular collapse. Temperatures of 46° to 50°C (115° to 122°F) were identified as causing systemic hyperthermia while temperatures of 60° to 75°C (140° to 167°F) caused central circulatory failure (high potassium). The peripheral and central factors that were the cause of death at lower temperatures also come into play at the higher temperatures but are evidently secondary to the hyperpotassemia.

It has been alleged that victims of conflagrations sustain pulmonary injuries of equal or greater significance as far as survival is concerned than burns received on the surface of the body. To investigate this aspect of the problem, Moritz, Henriques and McLean[229] conducted experiments on the effects of inhaled heat on the air passages and lungs, utilizing dogs. In some conflagrations, death has been attributed to the inhalation of chemical irritants contained in smoke without the presence of excessive heat. In others, however, victims have been exposed to heat, various combustion products, and smoke all at the same time. The experimental work with dogs was designed to delineate the effects of the inhaled heat. Inhalation of heated air, steam, and flame indicated that the quantity of heat that can be stored in the volume of gas that constitutes a breath is remarkably small.

In these experiments, neither the skin nor the mucous membranes of the mouth or throat were exposed to heat. The upper respiratory tract was protected by a trans-oral cannula in such a manner that the first impact of the hot atmosphere during inspiration occurred below the vocal folds of the larynx (see Fig. 8, a diagram of the respiratory tract). Pulmonary injury occurred in the lungs of two of the five animals inhaling flame from a blast burner. Four out of six suffered lung injuries when steam was inhaled. In all other animals, injury was confined to the upper air passages. When such recognizable thermal injury was confined to the upper air passages, it was inferred that pulmonary infection was secondary to the aspiration of mucosal debris.

These experiments by Moritz, et al., demonstrated that on dogs, only when the original temperature of the air was high enough to produce almost instantaneous burning of the skin and upper respiratory mucosa was there sufficient residual heat in the air reaching the lungs to cause pulmonary injury. The experiments also demonstrated the importance of humidity in increasing the heat content of inhaled air. Dry air at 500°C did not injure the lungs or the lower trachea in three separate exposures. The maximum
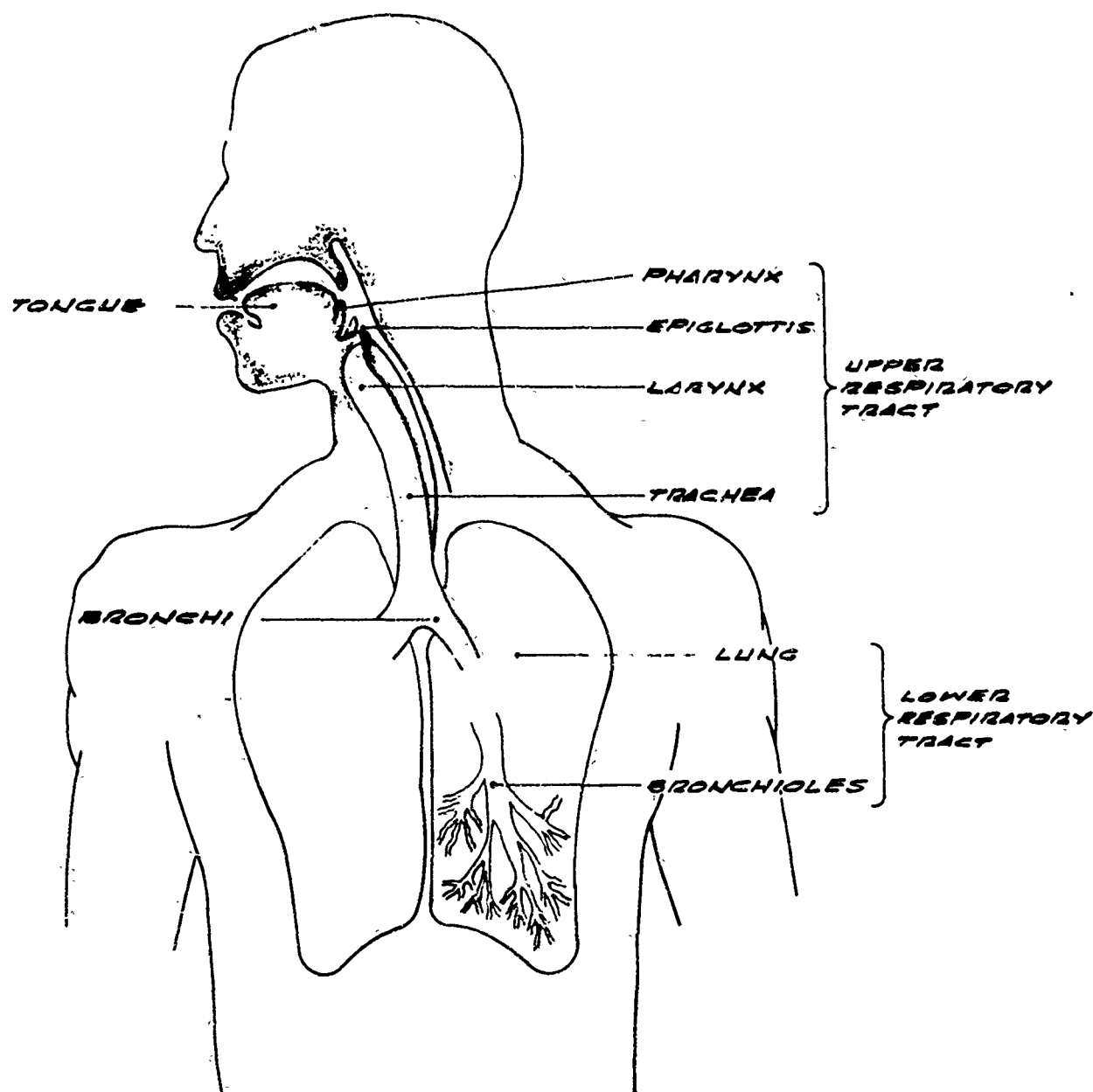
The mouth and nose lead to a hollow structure behind the soft palate which is called the pharynx, and here the respiratory and digestive tracts divide into separate tubes. The tube which leads to the lungs is called the trachea. Below the pharynx is the larynx, and in this organ are found the vocal cords, important to speech. The opening to the larynx can be partially closed by a lid of cartilage called the epiglottis. The area beneath the epiglottis and within the larynx is known as the glottis. The trachea is the long tube running down from the larynx in front of the esophagus (i.e., at the front of the neck). It divides at its lower end into two short tubes called the bronchi, which enter the lungs in their midportion at the midline of the chest. The bronchi divide and subdivide into shorter tubes called bronchioles which are within the lungs. The bronchioles ultimately divide into alveolar ducts from which lead air sacs or alveoli, which are the most important functional structures in the lungs. It is here that oxygen and carbon dioxide exchange between blood and air takes place. All the structures of the respiratory system are lined by a structure resembling the skin in many respects (respiratory epithelium), which secretes mucus.

Source: See Ref. (243)

FIGURE 8. DIAGRAM OF THE RESPIRATORY TRACT

temperature recorded in the lower trachea was 50°C during one exposure. When steam at 100°C was breathed, the lungs were injured in four out of six exposures; two were described as severe and the lower trachea was injured in all six exposures. Temperatures in the lower trachea of 53° to 94°C were recorded.

Air at 100°C will transport to the skin about 0.007 cal/cm^2-sec, and steam at 100°C will transport about 5 cal/cm^2-sec. This 700-fold increase in caloric bombardment is due to the latent heat of condensation of steam. This is why steam is an enormously greater hazard than hot air in the production of heat injury[150]. Within the range of their investigation, Moritz, et al., found that no type of thermal pulmonary exposure was encountered which was immediately incompatible with life. A thermal exposure sufficient to injure the lungs was more than enough to cause a rapidly fatal obstructive edema of the glottis.

The extent to which the results of these experiments can be applied to man is questionable. Since the dog has a relatively longer trachea than man, it seems that this would make him less vulnerable to thermal pulmonary injury. However, in pondering this question, Moritz, et al., concluded that "the elaborate precautions taken in the animal experiments to prevent loss of heat from inhaled air as it was conducted to the larynx would more than compensate for the shortness of the human trachea."

Webb[367] reports that test subjects voluntarily switched from nasal breathing to mouth breathing at 125°C (260°F) and that at 150°C (300°F) even mouth breathing became difficult. Pesman points out that neither experimental work nor experience data indicate a sharply defined respiratory threshold temperature[268].

Pesman also reports that the highest human respiratory system exposure without injury was 200°C (390°F). This temperature was chosen by him as a respiratory threshold temperature value to permit a gross comparison of skin injury and respiratory damage. Buettner[52] reports that when the air has a temperature of about 250°C (482°F) respiration is not particularly affected for several minutes except for the first breath which gives a sensation of heat in the nasal passages. Collins discusses the hesitance created by sudden breathing of heated air which could easily cause a person to pause long enough to allow the systemic effects of heat and combustion products to produce collapse and unconsciousness[77].

Webb[367] determined human tolerance times for nude men exposed to various heating transients ranging from 8°C/min (15°F/min) to 55°C/min (100°F/min). These exposures resulted in intolerable pain at temperatures between 160° and 200°C (320° and 390°F). The faster the rate of temperature rise, the higher the temperature which could be tolerated. Figure 9 shows a plot of Webb's results.
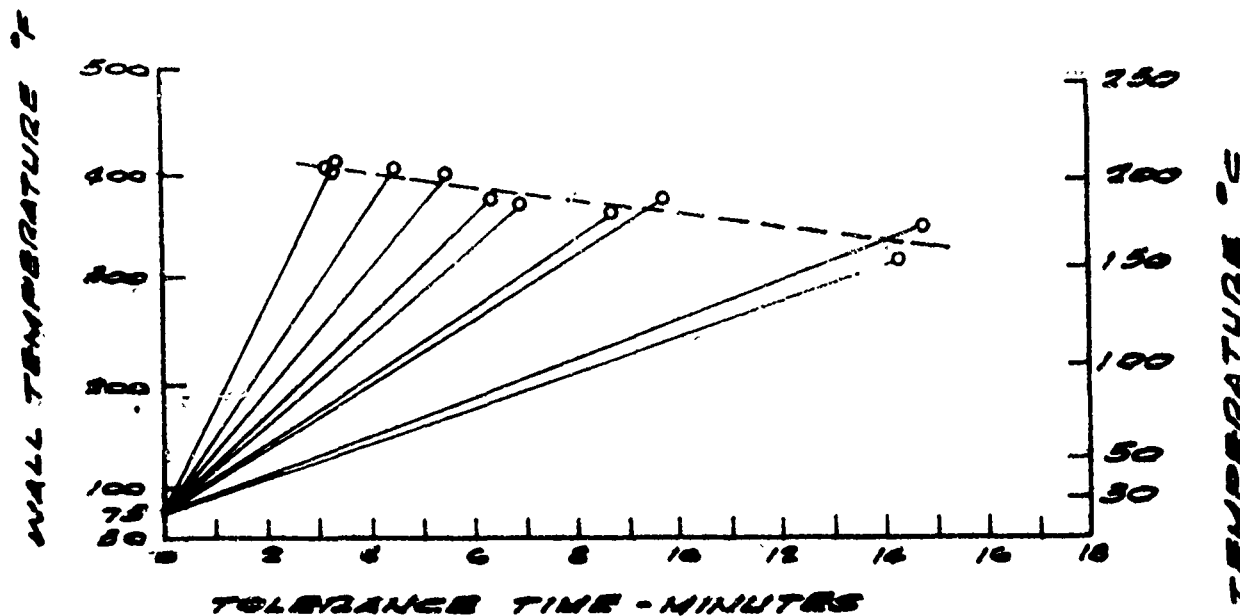
Source: See Ref. (367)

FIGURE 9. HUMAN TOLERANCE TO VARIABLE
HEAT PULSES

For longer exposures to lower temperatures, Miller and
Keer[223] note 50°C (122°F) as the critical temperature for survival. Strope
notes 35°C (95°F) as the limit of heat prostration and 30°C (86°F) as the
temperature above which the heat balance of the body cannot be maintained.[328]
The temperature limit of 30°C (85°F) has been suggested by many as the
maximum that can be endured for fourteen days. Johnson and Ramskill[159]
note that experimentation has shown that highly motivated healthy young
men had reached their limit of endurance after about one week at an average
effective temperature of 30°C (85°F). Brand-Persson[35] notes that a temper-
ature of 28°C (82°F) is bearable for long durations only if vigorous circulation
is maintained. Strope suggests 27°C (80°F) as the limit for a two-week
period.[328-332] Under ordinary circumstances, the temperature range of
10° to 25°C (50° to 78°F) is acceptable and 19° to 22°C (66° to 71°F) is
optimum[384] at a relative humidity of less than 50 percent.

Balke[19] provides a description of terminal heat stress and
notes that: "Heat tolerance tests are usually terminated when the experi-
mental subjects' pulse rate has risen to a frequency of 160 beats per minute,
almost to three times the resting value. Blood pressure at that point is
usually increased also. Cardiac output, therefore, must have been increased
close to three times the resting value of about 7 liters (0. 25 cu ft) per minute,
i. e., to 21 liters (0. 74 cu ft) per minute. Most 'normal' men of 'average'
physical condition have only a potential capacity for 25 liters per minute total
blood flow. Therefore, there are not many reserves left at extremely high

temperatures, and the slightest additional stress, requiring further circulatory adaptions, might complicate the situation beyond possible physiological solutions. "

The limits of tolerance observed by Blockley and Taylor[25-29] were determined by rectal temperatures of 39°C (102°F), skin temperature of 42°C (107°F), and a pulse rate of 150 to 160 beats per minute.

Based on this review of the literature, Figures 10 and 11 are presented as composites of the experimental work conducted to date. From these charts, points of interest can be easily established.

2. Radiant Heat

The previous discussion has been primarily concerned with heat transfer to the body by convection. Another important mode of heat transfer which must be considered is radiation. Buettner has stated that radiant heat from sources cooler than about 1500°C (2732°F) is nearly completely, in fact to 97 percent, absorbed by human skin.[57] Buettner states that, in tests performed with open gasoline fires (simulating an airplane crash), the heat transfer by radiation was at least four times greater than that by convection for a black cylinder within the flame.[54] For given conditions, such as people at rest in a normal room, radiated on the forearm, the prepain time depends in a simple way on the heat supply. Figure 12 is a plot of the radiant exposure versus prepain time. Buettner defines prepain time as, "the period extending from the beginning of exposure until the onset of unbearable 'stinging' pain. "[52]

Buettner has identified the minimum radiation intensity required for pain at 0.033 cal/cm^2-sec and the maximum intensity above which evaporative cooling has no effect at 0.083 cal/cm^2-sec. Exposure to less than 0.033 cal/cm^2-sec is low enough to allow the human body to defend itself by peripheral circulation and sweating, thus preventing the occurrence of pain. Exposure to radiation level of 0.032 cal/cm^2-sec on a sunny day may not cause pain within 15 or 20 min but will injure the skin as a common sunburn will, i.e., it cannot be endured for long.[219]

Below levels of heat which cause pain, continued application of sufficient heat will cause collapse. The time required for collapse depends on sweating, precooling and peripheral circulation.

Buettner cites radiation measurements from fires which indicate 600°C (1100°F) as a mean value for wood fires and 700°C (1300°F) as a mean value for gasoline fires. In addition, he cites the importance of radiation at all points around and above a fire while convection is only important downwind and above the fire.

49

300°C

EXTREMELY RAPID BURNS TOLERANCE TIME STRONGLY DEPENDENT ON PROTECTIVE CLOTHING

500°F

250°C

2-3 MIN TOLERANCE TIME WITH WET CLOTHING

400°F

TOLERANCE TIME LESS THAN 4 MIN WITH WET SKIN RESPIRATORY SYSTEM THRESHOLD 200°C (390°F)

200°C

IRREVERSIBLE INJURY TO DRY SKIN IN 30 SEC 180°C (360°F)

RAPID UNBEARABLE PAIN TO DRY SKIN 160°C (320°F)

MOUTH BREATHING DIFFICULT TEMP. LIMIT FOR ESCAPE 150°C (300°F)

150°C — 300°F

5 MIN TOLERANCE TIME 140°C (284°F)

NASAL BREATHING DIFFICULT 125°C (260°F)

15 MIN TOLERANCE TIME 120°C (248°F)

20 MIN. TOLERANCE TIME 115°C (240°F)

25 MIN TOLERANCE TIME 105°C (220°F)

VERY RAPID SKIN BURNS IN HUMID AIR 100°C (212°F)

100°C

200°F

49 MIN TOLERANCE TIME 82°C (180°F)

EXPOSURES ABOVE 65°C (144°F) RESULT IN CENTRAL CIRCULATORY FAILURE - HYPERPOTASSEMIA

60 MIN TOLERANCE TIME 70°C (158°F)

EXPOSURES BELOW 65°C (144°F) RESULT IN SYSTEMIC HYPERTHERMIA, PERIPHERAL VASCULAR COLLAPSE

HEAT STROKE 60°C (140°F)

3-5 HR TOLERANCE TIME 50°C (122°F)

50°C — 3-5 HR TOLERANCE TIME 50°C (122°F)

100°F

DANGER OF HEAT STROKE 32°C (90°F)

HEAT PROSTRATION 35°C (93°F)

ACCEPTABLE MAX FOR ACTIVITY AS ANTICIPATED IN MASS SHELTER, IMPOSSIBLE TO WORK EFFICIENTLY 29°C (85°F)

HEAT BALANCE CANNOT BE MAINTAINED 30°C (86°F)

SLEEPLESSNESS, HEAT RASHES, LIMIT FOR 14 DAYS 27°C (80°F)

PERSPIRATION BEGINS, DESIRABLE MAXIMUM FOR SHELTER 25°C (78°F)

OPTIMUM RANGE 19-22°C (66-71°F)

ACCEPTABLE RANGE 10-25°C (50-78°F)

0°C — 32°F

FIGURE 10. PHYSIOLOGICAL EFFECTS OF ELEVATED TEMPERATURES

50
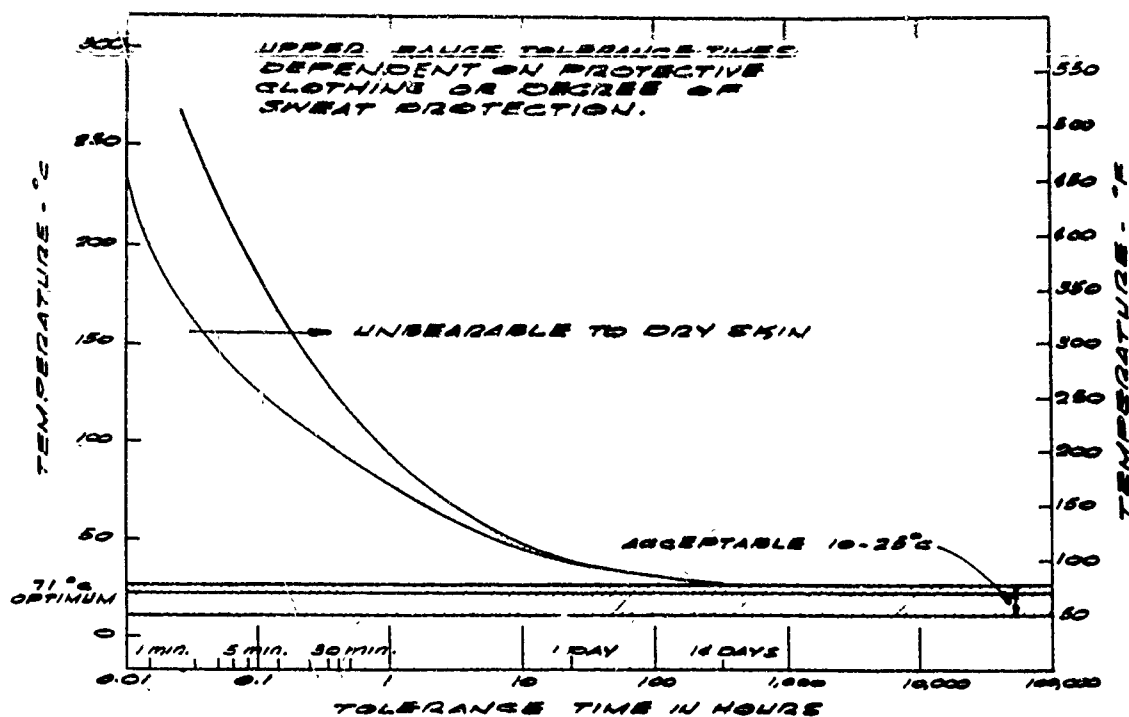
FIGURE 11. HUMAN TOLERANCE TO ELEVATED TEMPERATURES
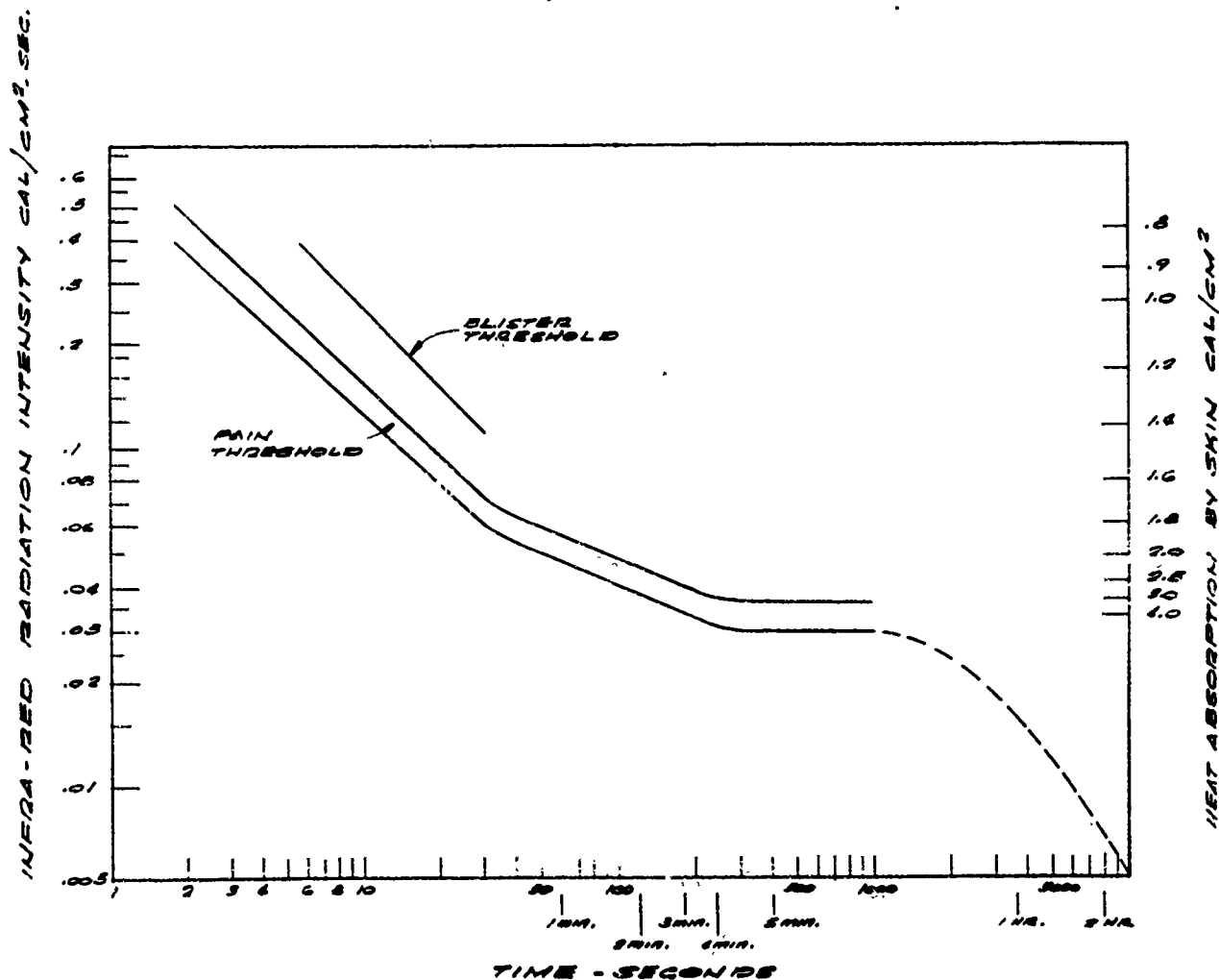
Source: See Ref. (52, 268, 326)

FIGURE 12. HUMAN RESPONSE TO HIGH RADIANT ENERGY

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The amount of radiation (radiation intensity multiplied by time) necessary to reach the pain threshold increases as the radiation decreases. This is apparent from Buettner's curve, Figure 12. In his experiments, Buettner applied radiation to the lower arm with its blood supply arrested by a tourniquet. Above 0.04 cal/cm^2-sec, no effect of the blood supply on the prepain time and on the skin temperature reached at the pain threshold could be detected.[52] Wetting the skin with water was also expected to offer protection. However, this cooling hardly exceeds 0.017 cal/cm^2-sec and offers protection from weak radiations only. For radiations of 0.25 cal/cm^2-sec or greater, wetting has no effect.

Experiments by Moritz, et al.[232], estimated the radiant and ambient caloric uptake rate per square centimeter per minute of pig skin when the surface temperature was 35°C (93°F). During the heat exposure, the surface temperature increases with time which results in a corresponding decrease in the rate of caloric uptake. For cutaneous surface temperatures not greater than 60°C (140°F), the rate of caloric uptake was directly proportional to the difference between the temperature of the surrounding air and that of the skin surface of the animal. At temperatures of 70°C (158°F) and higher, the infrared radiation from the walls of the test enclosure was the principal source of the heat energy absorbed by the animals. Under conditions that produced an air temperature of 70°C (158°F), 50 percent of the caloric uptake was by radiation. At 500°C (932°F), the caloric uptake by radiation represented 85 percent of the total. Thus, under long term exposures which must by necessity be at lower temperatures, radiant energy is less important and only appears to be significant under higher temperature conditions where the exposure to living persons will be shorter.

The solid curves in Figure 12 are plotted from Buettner[52], Pesman[268], and Stoll[326], and the dotted line is an extension of their work based on the temperatures of equal effectivity established by Buettner.[52]

3. Conductive Heat

In addition to the convective and radiant heat, conductive heat must also be recognized in a mass fire environment. Conductive heat is considered to be a factor only in those cases where people are trapped or are unconscious or immobile and subjected to immediate contact with heated objects. It is assumed that in any other situation, persons so exposed to conductive heat could remove themselves or the object from such contact. It is also possible to receive conductive heat burns from hot flying debris; however, the injury received from impact of the debris on the body is considered to be more important.

In heat transfer by direct contact, the surface heat conductance becomes almost infinitely large. In this regard, skin contact with objects at

a temperature of 44°C (111°F) or higher must be considered as possible sources of injury. Moritz exposed porcine skin to heated water at temperatures of 44° to 100°C (111° to 212°F) and recorded second and third degree reactions of complete epidermial necrosis at intervals of 7 hr to 1 second. In addition, a series of thirty-three exposures was made on human volunteers at temperatures of 44° to 60°C (111° to 184°F). These resulted in second and third degree reactions of complete epidermal necrosis being recorded in exposures of 5 hr to 1 second. [230]

Severe burns were sustained without discomfort at 47°C (142°F), and intense discomfort was sometimes complained of before any irreversible injury had been sustained at temperatures in excess of 48°C (144°F).

Figure 7 presents the results of Moritz' and Henriques' work in terms of time-surface temperature thresholds at which cutaneous burning occurs. Thus, when contact is made and the surface skin attains the temperature of the conducting object, the same rules apply as noted in the first part of this section on skin temperature.

In terms of the mass fire life hazard, the preceding section describes various physiological limits to heat, both convective and radiant. To summarize, the exposure limits for man may be estimated for different time periods representing different survival situations. Table 10 outlines such an estimate for heat.

TABLE 10. TEMPERATURE EXPOSURE LIMITS
FOR VARIOUS TIME PERIODS

Length of Exposure	Temperature Limit
5 min	140°C (284°F)
30 min	100°C (212°F)
2 hr	65°-80°C (150°-175°F)
4-8 hr	46°-65°C (115°-150°F)
27-72 hr	35°-41°C (95°-105°F)
14 days	27°C (80°F)

Examined in light of the heat to be expected within a firestorm (see Section III) where temperatures of 300° to 400°C (572° to 752°F) may exist for periods in excess of man's survival limits at these temperatures (see Figs. 10 and 11), there does not appear to be any chance for escape. This conclusion appears to be in agreement with many of the observations in Hamburg where people were seen to collapse after taking but a few steps. At these temperatures, the radiant energies above would be sufficient to cause unbearable pain in less than 7 seconds. Protection is clearly necessary in such an area.

C.   Carbon Monoxide

Almost any combustible material encountered in building construction will produce copious quar..ities of carbon monoxide with incomplete combustion.[385] The gas is colorless, practically odorless, and is slightly lighter than air (density = 0.967). The action of carbon monoxide on the human body, as it is understood today, will be discussed in this section.

It is generally agreed that carbon monoxide, unlike most poisons, is not lasting in its effects, unless the dosage has been so severe that secondary symptoms have been caused, as in the case of damage to the brain cells.[225] Cortical tissue does not recover if it is deprived of oxygen for more than 5 to 10 min, while, in certain other parts of the brain and spinal cord, irreversible changes do not begin to occur for periods as long as 20 to 30 minutes.[211]

Strictly speaking, carbon monoxide should not be classed as a poison but as a chemical asphyxiant. Carbon monoxide causes the symptoms of asphyxia by reason of the chemical reaction which takes place between carbon monoxide and the hemoglobin of the blood. Carbon monoxide displaces oxygen from hemoglobin, and, in turn, oxygen may again displace carbon monoxide and restore to the hemoglobin its oxygen carrying capacity even though blood has a greater affinity for carbon monoxide than for oxygen[93, 137, 149]. The reaction may be represented as:

$$HbO_2 + CO \rightleftharpoons HbCO + O_2 \tag{8}$$

where Hb is the hemoglobin.

The factors determining the direction of the reaction are the relative amounts of the two gases to which the blood is exposed in the lungs, i.e., their mass actions and their relative affinities for hemoglobin[149].

Carbon monoxide has an affinity for hemoglobin, estimated to be 210 to 300 times greater than oxygen.[149, 319, 373] Several other factors combine to govern the overall toxicity to an individual. The most important are: (1) the concentration of carbon monoxide in the inspired air, (2) duration of exposure, (3) respiratory time/volume of air, (4) cardiac output, (5) oxygen demand of the tissues, and (6) the hemoglobin concentration of the blood.[385]

The physiological effect of carbon monoxide on the human body has been defined in two separate ways by the many investigators: (1) in terms of the percent of carbon monoxide in the inspired air, and (2) in terms of the blood saturation (carboxyhemoglobin). The following paragraphs briefly discuss the values determined by several investigators for each method and present their results in graphic (Figs. 13 and 14) and tabular (Table 11) form.
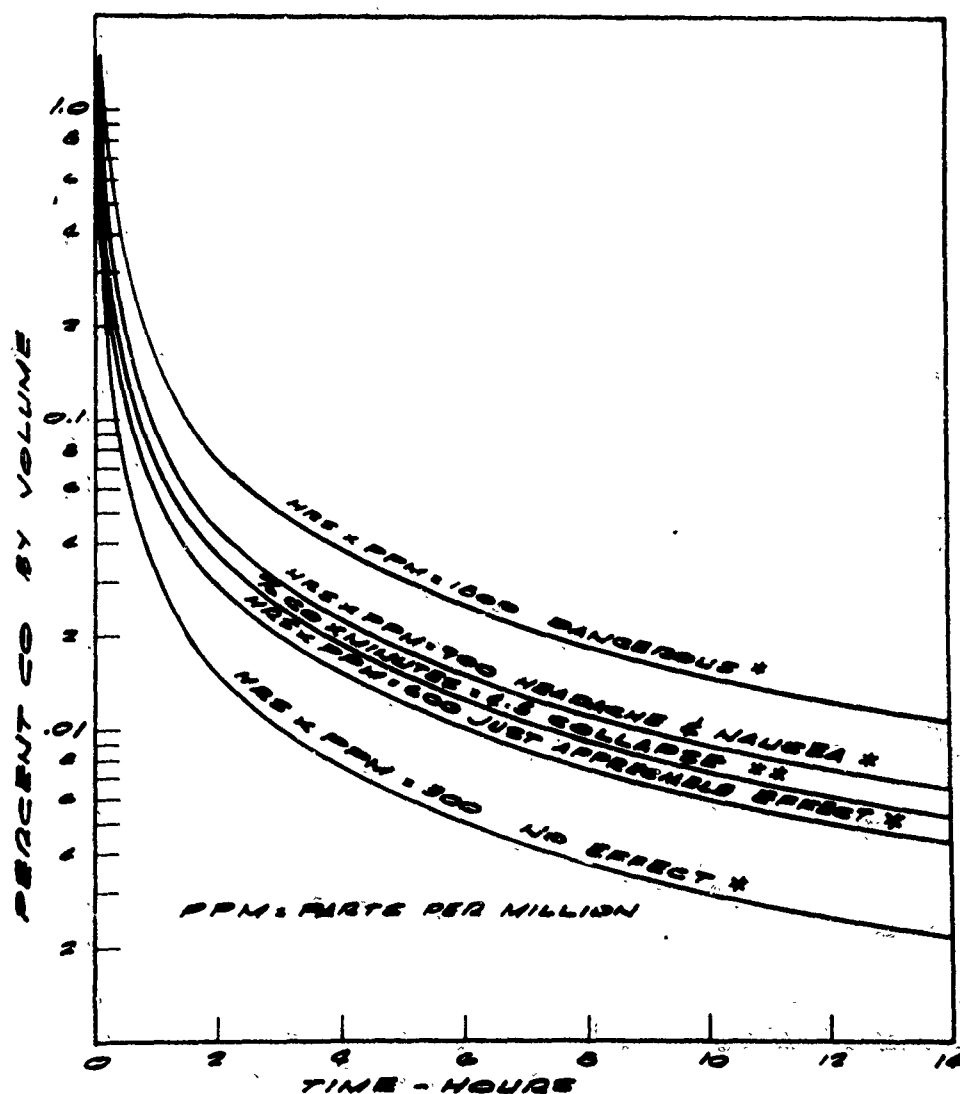
Source: *See Ref. (149)
       **See Ref. (225)

FIGURE 13. EFFECTS OF CARBON MONOXIDE

Henderson and Haggard have defined the effects of exposure in terms of time in hours and carbon monoxide concentration in parts per million (see Fig. 13). (149)

Time (hr) $\times$ concentration (ppm) = 300 (no perceptible effect)

= 600 (a just perceptible effect)

= 900 (headache and nausea)   (9)

= 1500 (dangerous)

Note: ppm represents parts per million; ppm $\times 10^{-4}$ = percent carbon monoxide in air.

Minchin reports that collapse will occur when the product of the carbon monoxide concentration in percent and time of exposure in minutes equals 4.5.[225] That is,

$$\int_0^t K_{CO}\, dt = 4.5 \tag{10}$$

This line is also drawn on Figure 13 for comparison.

The relationships reported by Henderson and Haggard[149] and Sayer and Davenport[302] are outlined in Table 11 in terms of the percent of the carboxyhemoglobin blood saturation that results from various carbon monoxide concentrations in air and the associated physiological effects.

The blood saturations are a direct result of the carbon monoxide concentrations in the air. Table 11 and Figure 14 reflect the relationship
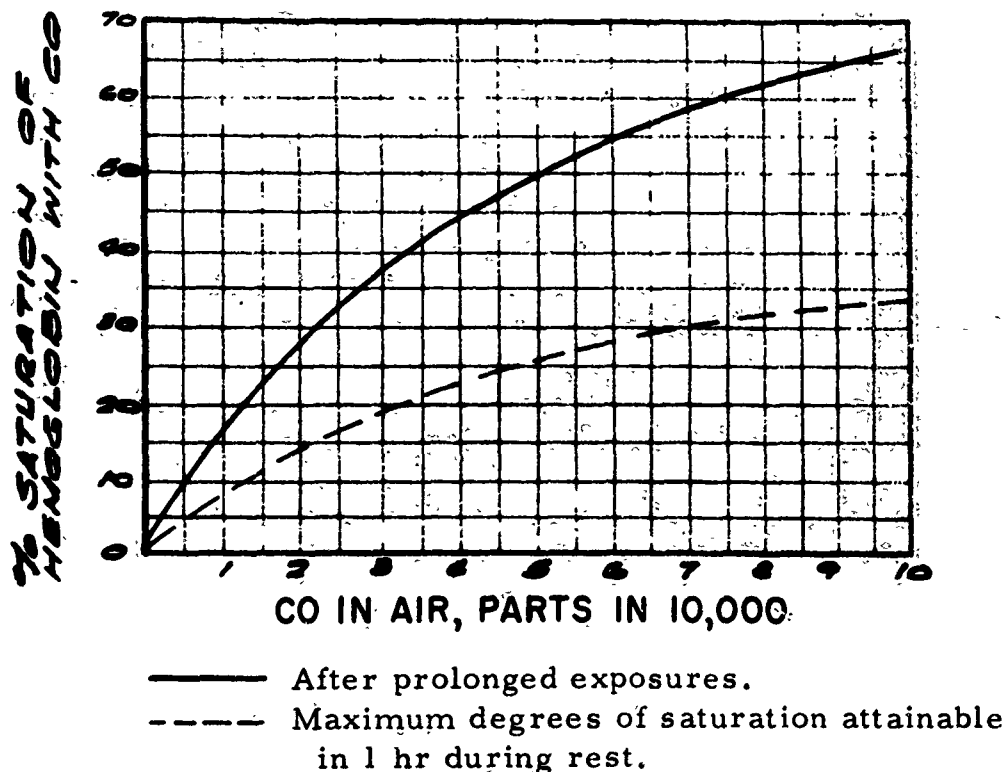
— After prolonged exposures.
--- Maximum degrees of saturation attainable in 1 hr during rest.
Source: See Ref. (149)

FIGURE 14. PHYSIOLOGY OF CARBON MONOXIDE

between these two factors as reported by several investigators. These same investigators report that the absorption of carbon monoxide in the blood is related to the respiration rate in that, when it increases, the rate of blood saturation also increases. Pesman has assigned values to various respiration rates in terms of activity[268] so that:

$$COHb = K \cdot CO \cdot t \tag{11}$$

TABLE 11. PHYSIOLOGICAL EFFECTS OF CARBON MONOXIDE ATMOS

Relationships of (COHb) Blood Saturation with Physiological Effects			Blood Satn. at Equil.(%) (149)	CO in-Air (%) (ppm)		Relationships of Carbon Monoxide in Air	
Henderson and Haggard[149]	Sayers and Davenport(302)*	Haldane and Priestly[137]				Henderson and Haggard[149]	Hamilton
10% — No appreciable effect except shortness of breath on vigorous muscular exertion.	0-10% — No symptoms		10	0.005	50†		
				0.006	60		
	10-20% — Tightness across forehead, slight headache, dilation of cutaneous blood vessels.	Below 20% — No perceptible effect.		0.007	70		
				0.008	80		
				0.009	90		
				0.010	100‡	0.01% — Concentration allowable for an exposure of several hours.	
20% — No appreciable effect in most instances, except shortness of breath, even on moderate exertion; occasionally slight headache.		20% — Exertion causes dizziness, extra palpitation and hypernoea	20				
	20-30% — Headache, throbbing in temples.			0.02	200		0.02% — Possible headache after
30% — Decided headache; irritable; easily fatigued; judgment disturbed.	30-40% — Severe headache, weakness, dizziness, dimness of vision, nausea and vomiting, collapse.	30% — Increased pulse rate, deeper breathing, palpitations, exertion causes dimness of vision and abnormal breathing and pulse rates	30	0.03	300		
40-50% — Headache, slight, confusion, collapse and fainting on exertion.	40-50% — Same as previous item with more possibility of collapse and syncope, increased respiration and pulse.	40% — Exertion causes fainting. Previous symptoms more marked.	40	0.04	400‡	0.04-0.05% — Concentration which can be inhaled for 1 hr without appreciable effect.	0.04% — From nausea after ital headache hr.
	50-60% — Syncope, increased respiration and pulse, coma with intermittent convulsions, cheyne-stokes respiration.	50% — Vision and hearing impaired, movements uncertain, exertion causes failure of legs and collapse. Breathing and pulse rate distinctly increased.	50	0.05	500		
				0.06	600	0.06-0.07% — Concentration causing a just appreciable effect after exposure of one hour	
			60	0.07	700		
60-70% — Unconsciousness, respiratory failure and death if exposure is long continued.	60-70% — Coma with intermittent convulsions, depressed heart action and respiration, possibly death.	56% — Impossible to stand or walk.		0.08	800		0.08% — Hea and nausea i unconsciou death in 2 hr
				0.09	900	0.10-0.12% — Concentration causing unpleasant but not dangerous symptoms after exposure of 1 hr.	
			70	0.10	1,000		
80% — Rapidly fatal.	70-80% — Weak pulse and slowed respiration, respiratory failure and death.					0.15-0.20% — Dangerous concentration for exposure of 1 hr.	0.16% — Hea and nausea i unconscious death in 2 hr.
Over 80% — Immediately fatal.	*Blood saturations are noted as 80% of approximate equilibrium values.			0.2	2,000		
				0.3	3,000		0.32% — Hea in 5 to 10 mi ness and dan 30 min.
				0.4	4,000	0.4% and above — Concentrations which are fatal in exposures of less than 1 hr.	
				0.5	5,000		
				0.6	6,000		0.64% — Hea in 1 to 2 min. and danger of min.
				0.7	7,000		
				0.8	8,000	†ACGIH Tentative Standard for 8-hr daily exposure. [79]	
				0.9	9,000	‡Long accepted maximum allowable concentration (MAC) for 8 hr. [9]	
				1.0	10,000		
				1.28	12,800	‡Long accepted MAC[9] for 1-hr exposure.	1.28% — Imm Unconsciousn breaths. Dan 1 to 3 min.
				2.0	20,000		Author cites l Henderson, H and Yant.

A

~cts ~stly[137]	Blood Satn. at Equil. (%) [149]	CO in Air (%)	CO in Air (ppm)	Relationships of Carbon Monoxide in Air with Physiological Effects		
				Henderson and Haggard[149]	Hamilton and Hardy[139]	Minchin[225]
		0.005	50‡			
	10	0.006	60			
		0.007	70			
ceptible		0.008	80			
		0.009	90			
		0.010	100‡	0.01% — Concentration allowable for an exposure of several hours.		0.01% — No effect. Allowable for several hours.
~es dizzi- ~on and	20					
		0.02	200		0.02% — Possible mild frontal headache after 2 or 3 hr.	0.02% — Headache after 2-3 hr; collapse after 4-5 hr.
~se rate, ~lpitations, ~ness of breathing	30					
		0.03	300			
	40					
~es fainting. more		0.04	400‡	0.04-0.05% — Concentration which can be inhaled for 1 hr without appreciable effect.	0.04% — Frontal headache and nausea after 1 or 2 hr. Occipital headache in 2-1/2 to 3-1/2 hr.	0.4% — Headache after 1 hr. Collapse after 2 hr. Death after 4-5 hr.
~aring ts uncertain, ~re of legs ~hing and increased.	50	0.05	500			
		0.06	600	0.06-0.07% — Concentration causing a just appreciable effect after exposure of one hour		0.06-0.07% — Headache after 45 min. Collapse after 1-1/3 hr. Death after 2-1/2 hr.
	60	0.07	700			
~ stand or		0.08	800		0.08% — Headache, dizziness and nausea in 3/4 hr. Collapse, unconsciousness and possible death in 2 hr.	0.08% — Headache after 30 min. Collapse after 1 hr. Death after 2 hr.
		0.09	900			
		0.10	1,000	0.10-0.12% — Concentration causing unpleasant but not dangerous symptoms after exposure of 1 hr.		0.1-0.12% — Headache after 20 min. Collapse after 45 min. Death after 1-1/4 hr.
	70			0.15-0.20% — Dangerous concentration for exposure of 1 hr.	0.16% — Headache, dizziness, and nausea in 20 min. Collapse, unconsciousness and possible death in 2 hr.	0.16% — Headache after 15 min. Collapse after 30 min. Death after 1 hr.
		0.2	2,000			0.20% — Headache after 10 min. Collapse after 20 min. Death after 45 min.
		0.3	3,000		0.32% — Headache and dizziness in 5 to 10 min. Unconsciousness and danger of death in 30 min.	
		0.4	4,000	0.4% and above — Concentrations which are fatal in exposures of less than 1 hr.		Author cites Henderson, Haggard, Haldane and Priestley.
		0.5	5,000			
		0.6	6,000		0.64% — Headache and dizziness in 1 to 2 min. Unconsciousness and danger of death in 10 to 15 min.	
		0.7	7,000			
		0.8	8,000	†ACGIH Tentative Standard for 8-hr daily exposure. [79]		
		0.9	9,000			
		1.0	10,000	‡Long accepted maximum allowable concentration (MAC) for 8 hr. [9]		
		1.28	12,800	‡Long accepted MAC[9] for 1-hr exposure.	1.28% — Immediate effect. Unconsciousness after 2 to 3 breaths. Danger of death in 1 to 3 min.	
		2.0	20,000		Author cites Haldane, Henderson, Haggard, Sayers, and Yant.	

where

COHb is percent of carboxyhemoglobin formed

CO is percent of carbon monoxide

t is exposure time in minutes

In this equation, the absorption constant, K, depends upon the volume of air required per minute by the exposed person. Sample K values for persons in various stages of activity are as follows:

K = 3 for persons at rest
     5 for light activity
     8 for light work
     11 for heavy work

Gettler[122] states that the average person in New York City has in his blood 1 to 1-1/2 percent carbon monoxide saturation. This figure is not related to exposure expressed as percent volume of air. Persons in a rural state institution have less that 1 percent, while New York street cleaners have as high as 3 percent. Gettler also questions the amount of carbon monoxide necessary in the bloodstream to produce death. Sayers and Yant state that 70 to 80 percent is necessary, and Henderson makes a similar statement (60 to 80 percent). Gettler reports on the analysis of over 2000 persons who died from exposure to carbon monoxide and points up fatalities with as little as 31.3 and 33.6 percent. Four and a half percent of the victims died with a carbon monoxide saturation of between 30 and 40 percent; another 4-1/2 percent between 40 and 50 percent; and 14-1/2 percent of the cases between 40 and 60 percent. So, all told, 23-1/2 percent of the victims died with less that 60 percent saturation. Gettler concludes that, with a saturation of up to 10 percent, no symptoms are manifest, but that, in the neighborhood of 20 percent, one gets shortness of breath and slight headache when doing muscular work. When approaching 30-percent saturation, the danger point is reached. Above 30 percent, death may result.

Drinker[93, 94] confirms Gettler's statements and reports on some experiments wherein humans were exposed to carbon monoxide. In these experiments, the subjects' blood saturation was raised to the 20- and 30-percent level. Only occipital headaches and vertigo were reported by these subjects. In addition, Haldane performed experiments on himself and inhaled carbon monoxide which brought his blood saturation up to 56 percent.[93, 137] The symptoms he recorded are also outlined in Table 11. There appears to be quite a divergence between Haldane's symptons and Gettler's conclusions.

The long accepted maximum allowable concentration of carbon monoxide in air for daily exposures not exceeding eight hours at any one time has been 0.01 percent[187] as published by the American Standards Association.[9]

Lindenberg reports that no clinical evidence is available which would definitely prove that such exposures are able to produce permanent physical or mental damage in man. [187]. Animal experiments, however, seem to indicate that such exposures may be harmful.

Lindenberg states that Lewey and Drabkin found morphologic damage to heart muscle and brain in dogs exposed to 0.01-percent carbon monoxide 5-1/2 hr per day, six days a week, during a period of eleven weeks. In monkeys exposed to 0.01 percent carbon monoxide for about three weeks, Lund and Wieland saw fatty degeneration and necrosis of the liver. On the other hand, Musselman and coworkers found that exposures of 0.005 percent carbon monoxide (50 ppm) for a period of three months caused no ill effects in dogs, rabbits, and rats. [187]

In the case of man, the most pertinent data which were found in the literature by Weeks [368] are those of Sievers published in 1942 who studied traffic officers on duty in the Holland Tunnel. These officers were exposed to about 70 ppm carbon monoxide daily, and their blood COHb concentration ranged from 0.5 to 13.1 percent of saturation and showed no abnormalities that could be attributed to carbon monoxide poisoning over a thirteen-year observation period. However, results obtained in intermittent exposures cannot be directly applied to continuous exposures.

Weeks states, "The slight changes or lack of positive toxic signs in dogs, rats, and rabbits suggest no harmful toxic effects from a continuous three-month exposure of animals to 50 ppm carbon monoxide. It would, therefore, seem, on the strength of comparable hemoglobin saturation in man as in dogs, that a concentration of 50 ppm carbon monoxide would be safe for continuous human exposure. "

There is a definite lack of data in the literature as to the long term chronic effects of continuous exposure of humans to carbon monoxide beyond eight hours. Most of the experimental work has been performed on the basis of intermittent rather than continuous exposures.

The anoxemia induced by carbon monoxide does not cease as soon as fresh air is inhaled, as is the case with the simple asphyxiants, but persists in diminishing degree until all the gas has been eliminated from the blood. With carbon monoxide, there is the additional disadvantage that in untreated cases the period of slow elimination is often much longer than the period of actual exposure in the atmosphere containing the gas. The displacement of carbon monoxide by oxygen is slow. [319] Henderson, et al. [149], concluded that after return to fresh air, the elimination of carbon monoxide through the lungs proceeds at a rate of 30 to 60 percent reduction of the blood saturation per hour.

Carbon monoxide is not a cumulative poison. There is no possibility that this gas can accumulate in the body. There is a possibility that chronic

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exposure to very low levels of carbon monoxide will acclimatize exposed
persons thus creating an increased tolerance to carbon monoxide. Sollman
reports that in work by Killick, Nasmith and Graham, and Haldane positive
increases in tolerance were indicated. [319] Drinker also reports that exposures
continued for weeks may result in quite unrecognized changes in an individual
that make him very resistant to the gas. [93] He cites experimental work by
Killick which demonstrated a reduction of blood saturation from 33 percent
to 18 percent in two exposures to 230 ppm of carbon monoxide after the
subject had been exposed to many exposures of carbon monoxide over a
period of eight months (intermittently). See Figure 15.
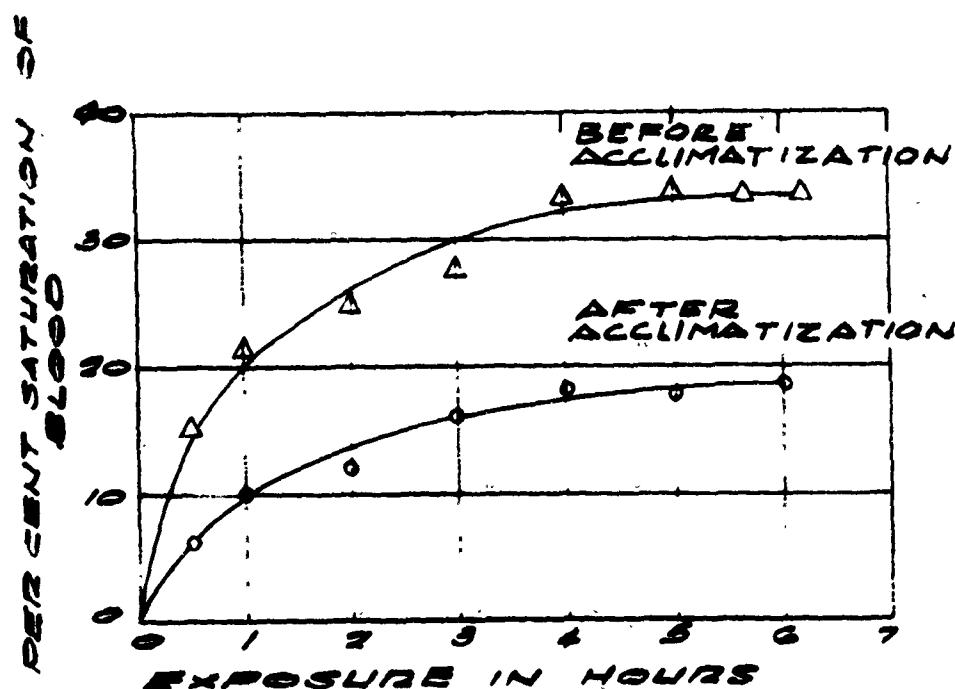
Source: See Ref. (93)

FIGURE 15.   ACCLIMATIZATION EFFECTS OF
CARBON MONOXIDE

Minchin reports that workers who habitually have, say, 10 percent of
their hemoglobin out of action from this cause seem to grow accustomed to the
situation so that their vulnerability is reduced. [225] Typical symptoms pro-
duced by breathing air contaminated with carbon monoxide gas, in ascending
order of severity, are: flushing of face, slight headache, weakness, dizziness,
nausea, vomiting, increased pulse and respiratory rate, unconsciousness,
and death.

To summarize the reports of the various investigators, Figure 16
is presented as a composite of their findings and may be used for reference
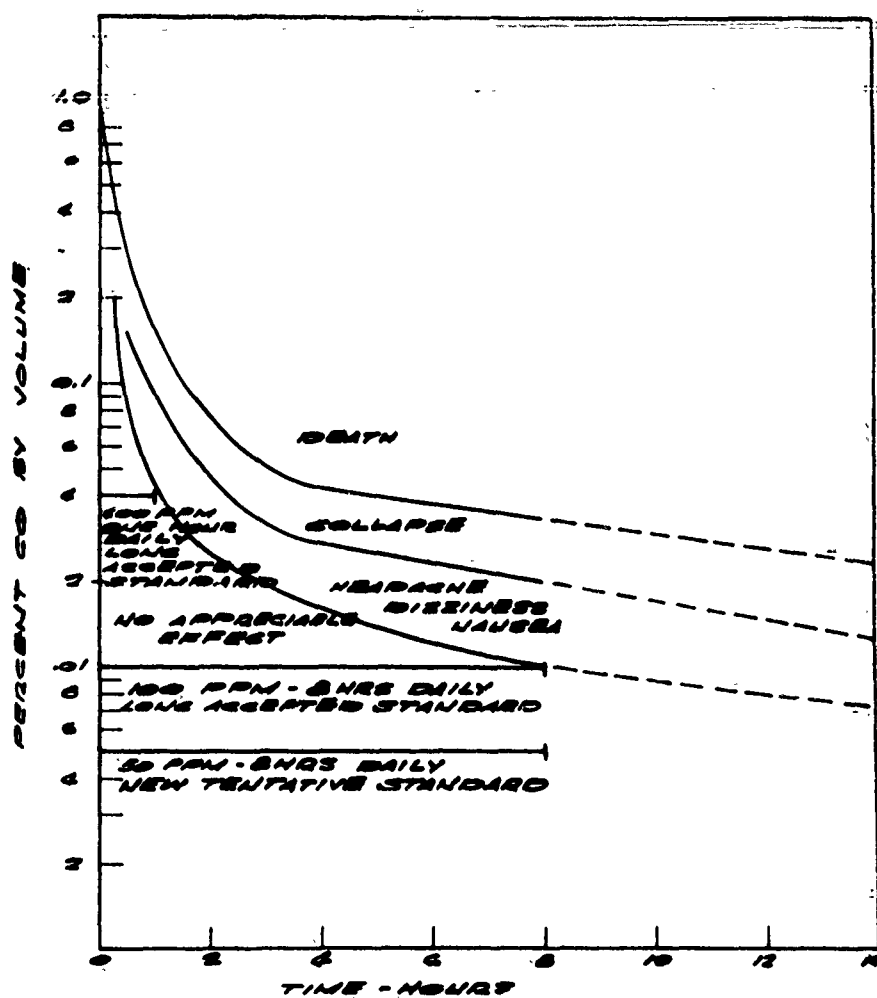
FIGURE 16.   PHYSIOLOGIC EFFECTS OF CARBON
MONOXIDE ATMOSPHERES

when considering the life hazard in the mass fire environment.   This figure
shows an extension of the physiological effects to chronic exposure beyond the
8-hr period in an attempt to define the mass fire life hazard to those trapped
in shelters for a longer period.   The formulas of Henderson and Haggard[149]
and also those of Minchin[225] obviously cannot be applied for an unlimited
period of time.   The range of their applicability has not been clearly estab-
lished.   For this reason, the curves in Figure 16 are presented as a dotted
line beyond an 8-hr period.

The effects of maximum carbon monoxide concentrations reportedly
recorded in open areas (see Section V) of 0. 08 percent would allow approxi-
mately a 1-hr exposure before collapse.   Thus, it appears that carbon monoxide
has yet to be shown as a serious hazard in the open.

On the other hand, the concentrations recorded on the criteria of
burning structures clearly show the need for adequate protection.   Table 12
presents the authors' conclusions regarding the allowable exposures to carbon
monoxide for various periods in terms of survival.

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TABLE 12. TOLERANCE TIMES FOR EXPOSURES TO CARBON MONOXIDE

Length of Exposure	Carbon Monoxide Limit (in Air)
5 min	0.30% 3000 ppm
30 min	0.15% 1500 ppm
2 hr	0.045% 450 ppm
4-8 hr	0.027-0.020% (270-200 ppm)
28-72 hr	0.012-0.010% (120-100 ppm)
14 days	0.005% 50 ppm

The exposure limits for periods in excess of 8 hr are simply estimates made by the authors and are not based on any experimental or recorded data.

In buildings where sheltered people will be exposed to carbon monoxide from interior fires, the life hazard will be quite severe. Any long term stay in the immediate building, if only for the duration of the fire which may be approximately 4-8 hr (considering cool down time to allow rescue-escape), would require that carbon monoxide levels be below 0.03 percent (300 ppm) to insure life safety.

D.   Oxygen

Normal inspired air contains 20.9 percent oxygen, whereas expired air contains 15.4 percent oxygen. The oxygen inhaled replaces that which is used in the combustion of the tissues. When there is insufficient oxygen in the air, as may happen in a fire situation inside a building, the body suffers oxygen deficiency – anoxia or hypoxia. The symptoms of anoxia develop so insidiously that the subject may be unaware of them. They arise chiefly from stimulation and depression of the central nervous system, since this is most susceptible to oxygen deficiency. [319]

When anoxia occurs rapidly, three typical stages may be distinguished. During the first stage, the respiration rate (particularly the inspiration rate) increases. In the second stage, the respiration rate becomes irregular and convulsive, the inspiration rate shallow and weak, the expirations powerful and prolonged, and consciousness is lost. The skin, especially the face, assumes a grey discoloration (as opposed to the blue coloring characteristic of asphyxia). The third stage is characterized by collapse and convulsions, depressed respiratory centers, shallow and infrequent respiratory movements, convulsive twitching of the extremities and the muscles of the face and neck, gasping movements, and the body is rigid and arched backward. In addition, the pulse is slow and soft, at first strong, then progressively weaker with the heart continuing to beat weakly for several minutes after the respiration has stopped. Artificial respiration during this interval generally results in recovery,

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but death usually occurs within six or eight minutes if the trachea is tied[319] (see Fig. 17).

If anoxia occurs slowly, the first symptoms are cyanosis and dyspnea on exertion. The individual becomes stupefied, but so gradually that he may not be aware of his condition. The stupor passes into unconsciousness and this into collapse. The motor symptoms may be entirely absent.[319] Kraines[173] describes both experimental and accidental exposures to low oxygen concentrations of 10 percent or less. Here, the subjects fell into a stupor, and the body and mind became feebler, little by little, gradually and insensibly. There was no suffering. In fact, the subjects felt an inner joy to the point of being gay, unaware of what was happening.

A candle is extinguished when the oxygen has fallen to about 17.5 percent, and is, therefore, a test for that safety condition. Different persons vary in their sensitiveness to oxygen deficiency.

Henderson and Haggard group the phenomena of anoxia into four stages, best reached when they develop slowly. These four stages are shown on Figure 17 with Sollman's data for comparison.

McFarland states that cortical tissue does not recover if it is deprived of oxygen for more than 5- to 10-min periods. In certain parts of the brain and spinal cord, irreversible changes do not begin to occur for as long as 20- to 30-min periods.[212]

In terms of the mass fire life hazard, oxygen reduction appears to be quite similar to carbon monoxide; the hazard in the open has yet to be demonstrated. However, it may be a serious factor within burning buildings. Table 13 presents examples of oxygen concentrations considered minimal for life support over various periods of time.

TABLE 13. TOLERANCE TIMES FOR EXPOSURE TO
REDUCED OXYGEN ATMOSPHERES

Length of Exposure	Oxygen Limit, %
5 min	9
30 min	11
2 hr	14
4-8 hr	15
24-72 hr	16
14 days	17

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HENDERSON & HAGGARD[149]   %O$_2$ BY VOL.   SOLLMAN[319]

NORMAL

21

20

19

18   AT 17.5% SLIGHT SYMPTONS

17

FIRST STAGE AT 16-12%   16
RESPIRATION VOLUME INCREASES
PULSE QUICKENS   15   AT 15% NO IMMEDIATE EFFECT
MUSCULAR COORDINATION DIMINISHED
ATTENTION & CLEAR THINKING   14
   REQUIRE MORE EFFORT

SECOND STAGE AT 14-9%   13
RESEMBLES ALCOHOLIC INEBRIATION,
HEADACHE, NUMBNESS, MUSCULAR   12
EFFORTS FATIGUE READILY AND CAUSE
FAINTING, CHEYNE-STOKES RESPIRATION   11

                                      10   AT 10% DIZZINESS, SHORTNESS
                                           OF BREATH, DEEPER AND MORE
THIRD STAGE AT 10-6%   FREQUENT RESPIRATION,
EXAGGERATES EARLIER SYMPTOMS   9   QUICKENED PULSE, SLIGHT CYANOSIS
NAUSEA AND VOMITING, EXERTION
IMPOSSIBLE, PARALYSIS OF MOTION   8
AND SENSATION, UNCONSCIOUSNESS   AT 7%, ABOVE SYMPTOMS BECOME
                                      7   SERIOUS AND STUPOR SETS IN,
                                           UNCONSCIOUSNESS OCCURS

FOURTH STAGE   6
BELOW 6%, RESPIRATION STOPS,
CONVULSIVE MOVEMENTS   5   AT 5% MINIMUM CONCENTRATION
HEART ARRESTED 6-8 MINUTES   COMPATIBLE WITH LIFE
AFTER THE RESPIRATION   4
                                           AT 3-2% DEATH WITHIN 45 SECONDS
                                      3

                                      2
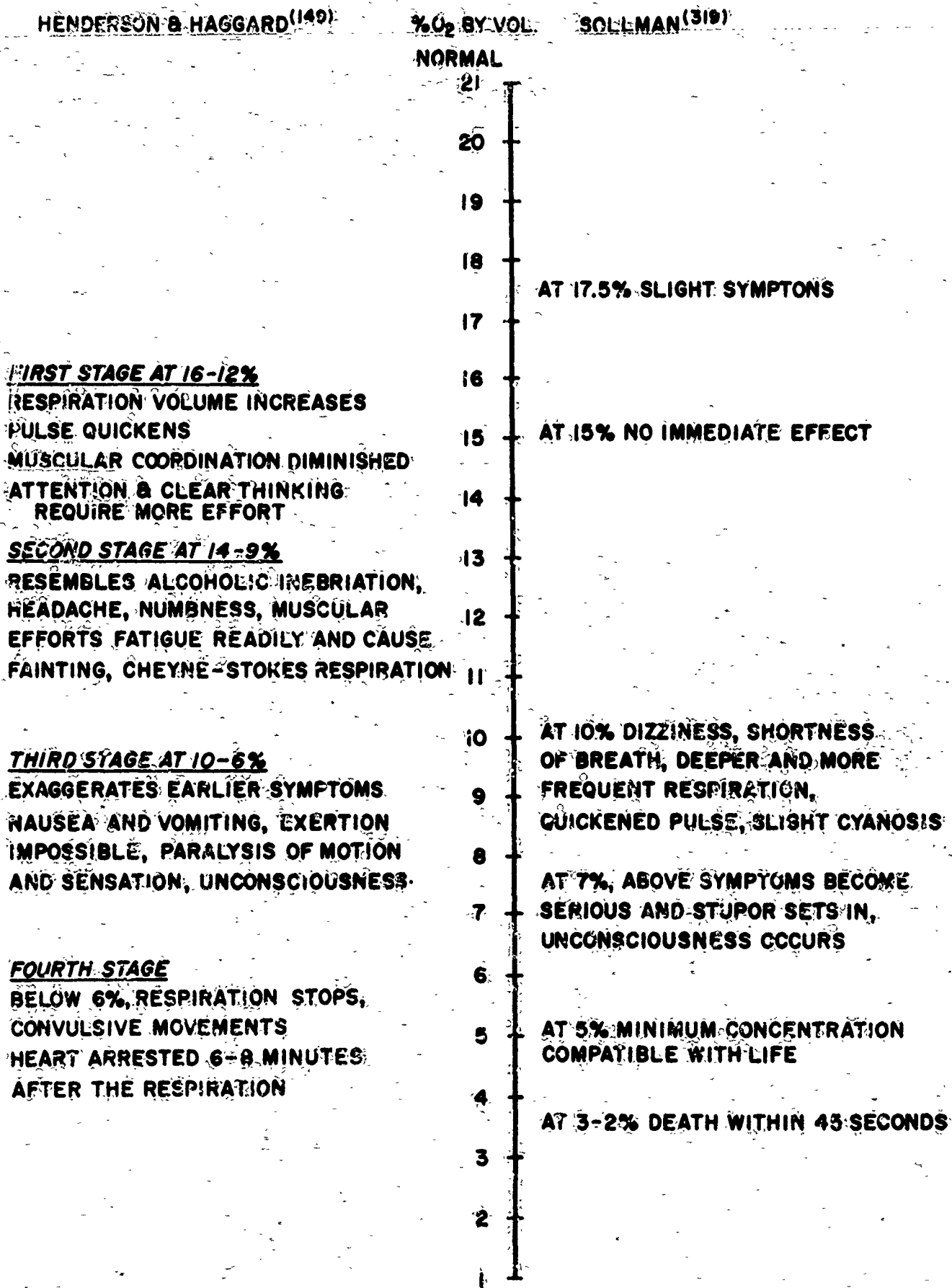
                                      1

FIGURE 17   EFFECTS OF REDUCED OXYGEN ATMOSPHERES

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E. Carbon Dioxide

Carbon dioxide is a colorless, odorless gas formed by oxidation, such as the combustion of fuel. It causes a stimulation of the respiratory center in the brain and, if breathed in excess, results in an abnormally high respiration rate. Carbon dioxide is ordinarily not considered to be a toxic gas. Carbon dioxide induces asphyxia through the exclusion of oxygen, which is accelerated in the early stages by the stimulating effect of the gas on the respiratory center, producing deeper and more rapid breathing. As little as 2 percent of carbon dioxide in the inspired air effectively stimulates respiration and 3 percent doubles the lung ventilation according to Viessman[359] (see Fig. 18).
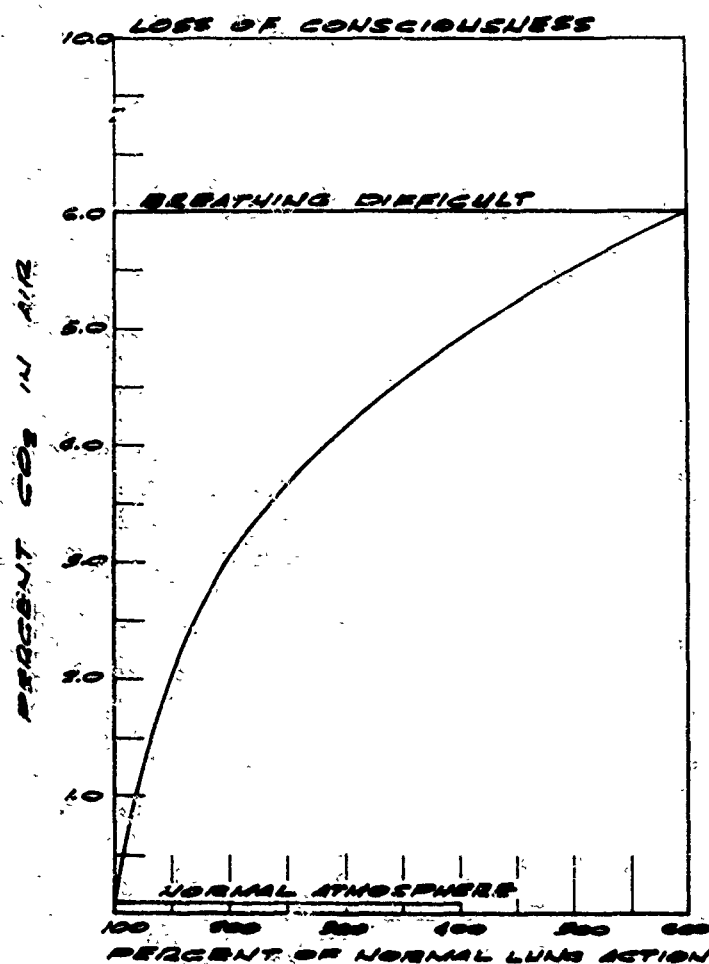
Source: See Ref. (359)

FIGURE 18. EFFECT OF CARBON DIOXIDE ON LUNG ACTION

A single publication issued by the U.S. Bureau of Mines lists two separate physiological effects versus various concentrations of carbon dioxide in air[226] (see Table 14).

TABLE 14. PHYSIOLOGICAL EFFECTS OF CARBO... C.

% CO by Volume	Sollman[319]	U. S. Bureau of Mines[226]	U. S.
0.04	No effects; normal air.		
0.05		Slight and unnoticeable increase in the ventilation of the lungs.	
0.5-0.8			
1.5			
2.0	Breathing deeper; tidal volume increased 30%.	50% increase.	Slight in... symptom... / Sli... syr...
3.0		100% increase.	
4.0	Breathing much deeper; rate slightly quickened; considerable discomfort.		
4.5-5.0	Breathing extremely labored, almost unbearable for many individuals, nausea may occur.		
5.0		300% breathing laborious.	Noticeab... lation, b... / Not... lati...
7-9	Limit of tolerance.		
7.2			Marked ... tion mod... fullness ... minutes... / Mar... tion... full... min...
9-10			300% inc... frontal h... sweating... / 300... fron... swe...
10.0		Cannot be endured for more than a few minutes.	
10-11	Inability to coordinate; unconsciousness in about 10 minutes.		
5-20	Symptoms increase, but probably not fatal in one hour.		
5-30	Diminished respiration; fall of blood pressure; coma; loss of reflexes; anesthesia. Gradual death after some hours.		

CARBON DIOXIDE CONCENTRATIONS

U. S. Bureau of Mines[226]	Schaefer[306]

<table>
<tr><td></td><td>The level at which probably no significant physiological, psychological, or adaptive changes occur.</td></tr>
<tr><td></td><td>The level at which basic performance and physiological functions are not affected. Under these conditions, however, slow adaptive processes are observed in electrolyte exchange and acid base balance regulations which might induce pathophysiological states on greatly prolonged exposure.</td></tr>
<tr><td>Slight increase; no subjective symptoms.</td><td></td></tr>
<tr><td></td><td>The level producing performance deterioration, alterations in basic physiological functions as expressed in changes of weight, blood pressure, pulse rate, metabolism and finally pathological changes.</td></tr>
<tr><td>Noticeable increase in lung ventilation, but no other symptoms.</td><td></td></tr>
<tr><td>Marked increase in lung ventilation moderate sweating and a slight fullness in the head after 10 minutes.</td><td></td></tr>
<tr><td>300% increase in lung ventilation frontal headache - dizziness, sweating - 10 minutes.</td><td></td></tr>
</table>

Sollman reports that at 4.5 to 5 percent carbon dioxide, the breathing becomes extremely labored, almost unbearable for many individuals, and nausea may occur.[319] At 8-1/2 percent carbon dioxide, there is distinct dyspnea, loss of blood pressure, and congestion which become unsupportable in 15 or 20 minutes, and the limit of tolerance is 7 to 9 percent. Balke reports the tolerance limit at 10 percent.[19]

Yuill and Bieberdorf state that inhalation of 7 to 10 percent carbon dioxide may be fatal in a short period.[385]

Viessman[359] suggests 3 percent as a practical limit for a 3-hr exposure. Strope[328] also suggests 3 percent as the practical limit in a shelter for periods up to 24 hours. Murphy[237] mentions 5 percent as the dangerous limit, while Marshall and Pleasants[208] report safe allowable concentration ranges to be from 5 to 7.2 percent with some slight physiological effects appearing dependent on the individual. They report that the average person will experience a slight fullness of the head and moderate sweating upon being exposed to 7.2 percent, the maximum allowable concentration ranges from 6 to 9.5 percent (at 8 percent, moderate headaches and dizziness occur; above 9.5 percent, severe headaches, dizziness and preliminary carbon dioxide narcosis will be encountered).

Leutz[181, 182] suggests 2 percent carbon dioxide as the bearable limit, and Panero[261] states that the carbon dioxide content should not be allowed to reach concentrations above 0.6 percent. After judging the wide variance in suggested limits from 0.6 to 7.2 percent, Muraoka[233] suggests that 1.5 percent appears to be a good design value.

Roth[290] presents a relationship between carbon dioxide concentration and time that explains some of the apparent disagreement (see Fig. 19). However, his upper limit for normal performance is approximately 1.5 percent carbon dioxide and from 3 to 4 percent for minor perceptive changes. Roth's data cover the 0 to 100-min time period.

Schaefer[306] presents a concept of triple tolerance limits for a time period up to 26 days based on chronic carbon dioxide toxicity studies (see Fig. 19 and Table 14).

The Navy has successfully conducted studies of man's exposure to 1.5 percent carbon dioxide for a continuous period of 42 days,[143] and the Air Force has recently exposed men to levels of 3 percent for a continuous period of 5 days. The 3-percent exposure was reported as "sort of a minimal challenge" to the human body.[189]

Pesman[268] reviewed the works of White, Spealman and King and developed a different set of limits (see Fig. 19). He concluded that, in concentrations up to and above 4 percent for periods of ten minutes, individuals could perform useful tasks.
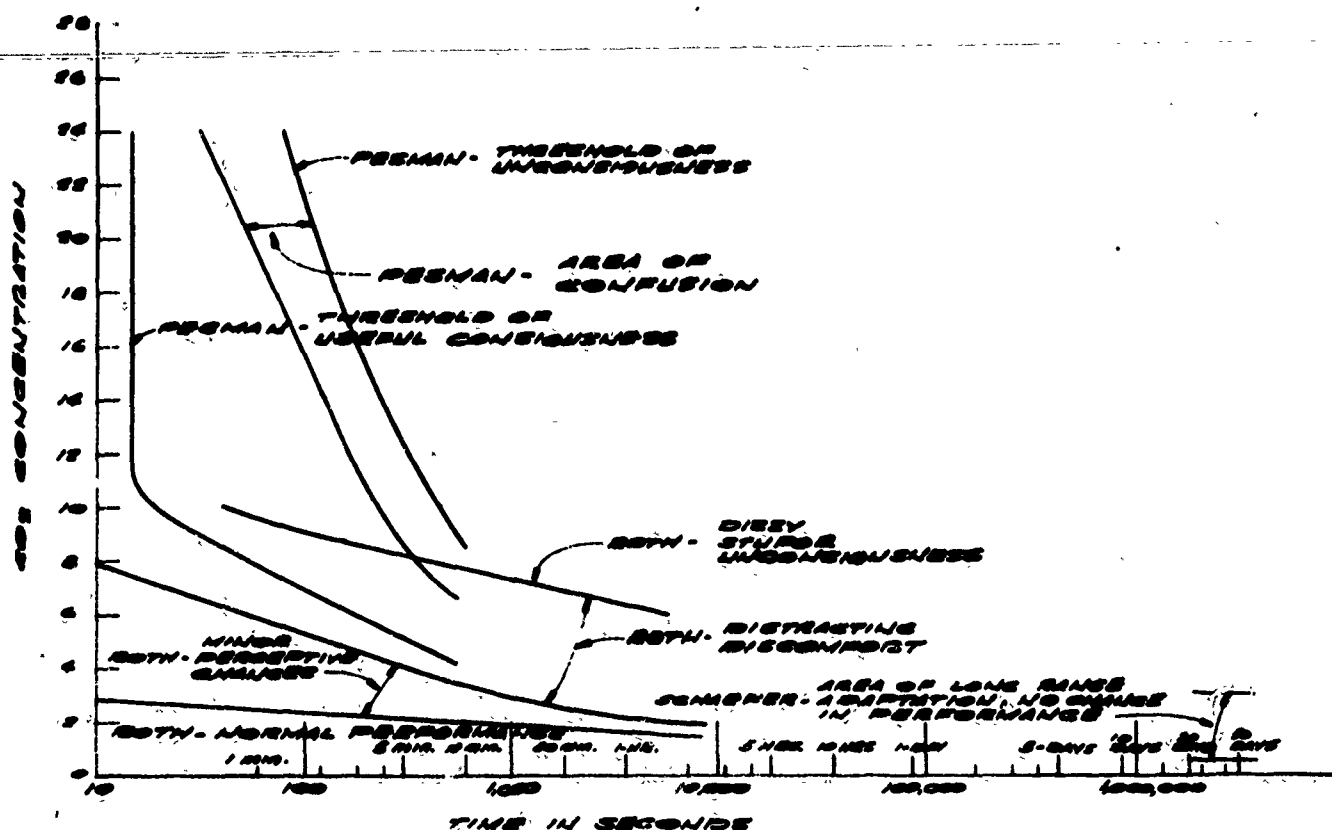
Source: See Refs. (268, 290, 306)

FIGURE 19.   THRESHOLD CURVES FOR EXPOSURE
TO CARBON DIOXIDE

Figure 19 presents a summary of the available data and represents the range of physiological effects generally known to date.

Summarizing, it would appear that there are many circumstances in poorly ventilated or overcrowded shelters where carbon dioxide may be a serious factor and one that certainly should be taken into account.

TABLE 15.   TOLERANCE TIMES FOR EXPOSURE
TO CARBON DIOXIDE

Length of Exposure	Carbon Dioxide Limit (In Air), %
5 min	5.0
30 min	4.0
2 hr	3.5
4-8 hr	3-2
24-72 hr	2.0
14 days	1.5

Table 15 gives an example of exposure limits that are allowable for the various periods of time without seriously endangering the health of those

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exposed. While all the investigators do not agree precisely, there is enough general agreement to incorporate their findings into one figure (see Fig. 20).
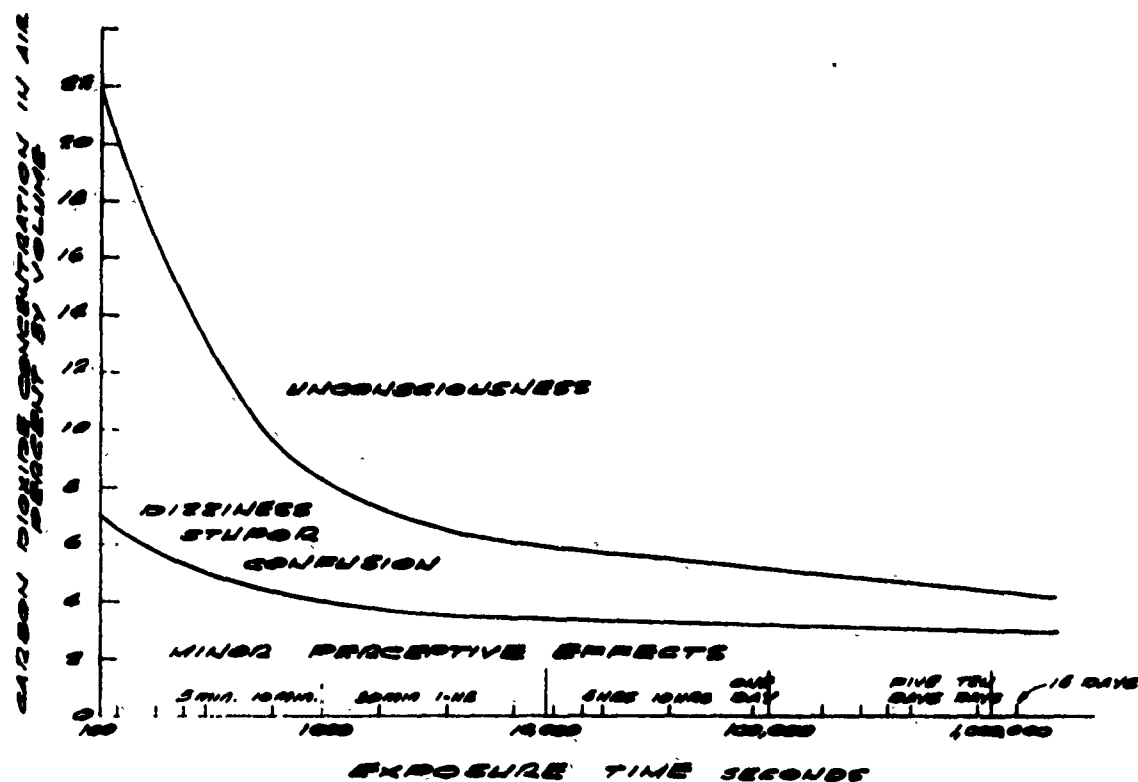
FIGURE 20. TOLERANCE LIMITS FOR EXPOSURE
TO CARBON DIOXIDE

On the other hand, it is impossible, obviously, to draw a distinct line between those situations where carbon dioxide can be considered by itself and the situations where oxygen deficiency is of prime significance. Anoxia is produced by a lack of oxygen while asphyxia is produced by a combination of carbon dioxide and oxygen deficiency. In either situation, carbon monoxide is likely to be present in some amount. Maintenance of a proper balance of the three gases, awareness of the effects of each, and means for knowing when the survivable limits of each are approached would seem to be an appropriate defense.

F.   Other Noxious Gases

In addition to the products of combustion already mentioned, there are a host of other noxious gases which may be encountered depending on the nature and quantity of the material being burned and the conditions of combustion.

The importance of hydrogen chloride (HCL), ammonia (NH_3), hydrogen sulfide (H_2S), chlorine (Cl), and a wide variety of other gases such as sulphur dioxide, phosgene, hydrogen cyanide, and the oxides of nitrogen has been cited as being of significance under special conditions. [95, 243, 385] The most recent of these references indicate that carbon monoxide, or a combination of carbon monoxide and oxygen deficiency, consititutes the major life hazard in most fires.

Quantities of certain materials in storage, as in warehouses or salesrooms, involved in fire may produce unusual quantities and possibly fatal amounts of gases other than carbon monoxide. For instance:

Chlorinated compounds - hydrogen chloride, chlorine, phosgene

Natural and synthetic rubber - sulphur dioxide and hydrogen sulphide

Natural fibers such as wool or hair - hydrogen cyanide

Even here, the nature of the fire (ventilation, ignition source, etc.) may be such that anoxia and carbon monoxide are far more significant.

It is possible, also, that individual gases present at a tolerable level may, in combination with other gases also present at an acceptable level, provide a fatal combination. The possibility of such synergistic action is considered in more detail below and in Section V.I.

An attempt will not be made in this report to define further the life hazard presented by these noxious gases, some of which have been mentioned, other than to include some of the more significant references which contain information regarding the various gases, how they are produced, and their relative toxicities.

Noxious gases (here defined as smoke, fumes, and products of incomplete combustion) have been cited many times as a major cause of death by Phillips[270-273], Finland[112], Davis[85], et al. The work conducted by Moritz, Henriques, and McLean[229] further points to the fact that many fatalities which are diagnosed as being due to respiratory burns are more frequently due to pulmonary edema and asphyxia resulting from the inhalation of either smoke or combustion gases. The difficulty in producing a primary pulmonary burn, as pointed out by Moritz and coworkers, emphasizes the fact that most of these cases of pulmonary edema may be secondary to the inhalation of noxious fumes. [85]

G.   Synergisms

The life safety hazard of various combustion products, each one being treated as a single exposure has been discussed in previous sections. It has been recognized by many investigators that significant synergistic effects

exist between the various individual component gases resulting from the burning of various building materials.

The combined action of oxygen and small amounts of carbon dioxide is probably one of the oldest known effects. In 1920, Henderson and Haggard published a paper on the treatment of carbon monoxide asphyxia by the inhalation of 90 percent of oxygen and 10 percent of carbon dioxide. In this case, the carbon dioxide serves to increase the breathing rate (pulmonary ventilation) and thus increase the rate of disassociation of the COHb. Tests reported by Gellhorn[121] show an effect from low oxygen (8.5 percent) which disappeared when a mixture of 8.5 percent oxygen plus 3 percent carbon dioxide was breathed. The carbon dioxide served to increase the pulmonary ventilation rate which offset the reduced oxygen atmosphere. Schaefer points out that this effect lasts only for two or three days and that this is then followed by a period of depression.

Zapp[386] exposed goats to atmospheres of low oxygen and then to atmospheres of low carbon monoxide. Following this, the goats were exposed to a combination of low oxygen plus carbon monoxide. Later, carbon dioxide and heat were added to determine their individual and combined effect.

The goats exposed to 3 percent oxygen in nitrogen died on an average in 6.91 minutes. Exposure to 2.7 percent carbon monoxide in air resulted in deaths at an average of 7.24 minutes. The combination of 2.7 percent carbon monoxide with 3 percent oxygen in nitrogen proved to be more lethal than either carbon monoxide alone or low oxygen alone. Respiration ceased at an average time of 1.9 min, and the last gasp occurred at an average of 4.8 min when the 2.7 percent carbon monoxide with 3 percent oxygen in nitrogen was used. During this test, arterial oxygen saturation reached a lower level (6 percent) and arterial carbon monoxide saturation reached a higher level (90 percent) after 5 min of gassing with this mixture than with either the low oxygen or the carbon monoxide component (see Table 16).

Some goats were then exposed to an atmosphere containing 2.7 percent carbon monoxide, 3 percent oxygen, and 7 percent carbon dioxide in nitrogen. The average time of death was 4.1 min with the 7 percent carbon dioxide having a slight and probably insignificant effect on the time of death of the goats. The arterial oxygen and carbon dioxide saturation were essentially the same as in the absence of carbon dioxide.

When the effect of artificial fever induced in the animals was combined with the toxicity of lethal gas mixtures, the average time of death was reduced by 39, 41 and 32 percent.

Pesman[268] has studied the escape time from aircraft as limited by the combination of carbon monoxide and low oxygen. Lower oxygen concentrations are related to high absorption factors which in turn reflect a higher percentage of carboxyhemoglobin being formed.

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TABLE 16. EFFECT OF LOW OXYGEN, HIGH CARBON DIOXIDE, HIGH CARBON MONOXIDE, AND HEAT ON GOATS AND PIGS

Gas Mixture	Goats							Pigs	
	2.7% CO in Air	2.7% CO 3.0% O_2 in N_2	3% O_2 in N_2	2.7% CO 3.0% O_2 7% CO_2 in N_2	2.7% CO in Air + Heat	2.7% CO 3.0% O_2 in N_2 + Heat	2.7% CO 3.0% O_2 7.0% CO_2 + Heat	2.7% CO 3.0% O_2 7.0% CO_2 in N_2	2.7% CO 3.0% O_2 in N_2
Number of Animals	5	9	3	5	3	8	2	5	3
Respiration Ceased, min	3.03	1.9	4.56	1.25	2.5	1.25	1.08	1.17	2.0
Last Gasp, min	7.24	4.8	6.91	4.1	4.4	2.85	2.78	4.3	4.2
Arterial Oxygen Saturation, %, during Gassing for:									
0.5 min	--	54	--	--	67.1	24	24	--	--
1.0	48.5	30	25.2	20	41.2	12.2	15	15	36
2.0	--	--	--	--	--	--	--	8	9
3.0	18.8	10	--	7	14.6	2.9	2.2	--	--
5.0	7.6	6	15.3	5	6.6	--	--	6	4
Arterial Carbon Monoxide Saturation, %, during Gassing for:									
0.5 min	--	--	--	--	21.4	13.7	27	--	--
1.0	44.2	48	--	72	44.6	29.3	48	76	49
2.0	--	--	--	--	--	--	--	84	78
3.0	74.2	82	--	89	71.8	37.8	49	--	--
5.0	86.2	90	--	91	79.2	--	--	88	92

Source: See Ref. (386)

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Moss, et al. [235], reported on the reactions of white female rats
to hydrogen cyanide, carbon monoxide, and mixtures of these two gases.
The experiments using carbon monoxide or hydrogen cyanide singly showed
that death of rats could not be regularly expected from hydrogen cyanide
under a concentration of 50 ppm (0.005 percent) or from carbon monoxide
under a concentration of 5000 ppm (0.5 percent). All the rats treated with
a carbon monoxide concentration less than 5000 ppm ultimately recovered.
When combined, a dose of 2000 ppm carbon monoxide to 20 ppm hydrogen
cyanide in one case produced death in approximately 30 minutes. When the
hydrogen cyanide was reduced to 15 ppm, death was once caused in 15
minutes. When reduced to 10 ppm of hydrogen cyanide, a death occurred
at 32-1/2 minutes. As a result of this work it was concluded that, in the
presence of sublethal amounts of carbon monoxide, a relatively small amount
of hydrogen cyanide proved fatal to rats.

Keplinger, et al. [167], studied the effects of environmental tempera-
ture on the acute toxicity of a number of compounds in rats. The approximate
lethal doses of fifty-eight compounds were determined at three different ambient
temperature conditions: 8°C (46.4°F); 26°C (78.8°F); and 36°C (96.8°F).
Nearly all rats in the hot environment succumbed to lower doses of a compound
than those at 8° or 26°C. Based on the lethal doses, the compounds were two
to seventeen times more toxic at 36°C than at 26°C.

Korenevskaya [172] (USSR) cites Razgulyaev and Karasik who concluded
that the concentration of carboxyhemoglobin in the blood in carbon monoxide
poisoning at high air temperature decreased. They assumed that the intensified
effect of carbon monoxide poisoning at high air temperature was the result of
lowered body resistance. Pokrovskii and Naviotskii were also cited as being
of the opinion that the concentration of carboxyhemoglobin in the blood at high
air temperature was not indicative of the degree of intoxication. Hyperthermia,
they believed, affected first the central nervous system, enhancing its
reactivity to the poisonous effects of carbon monoxide, thereby augmenting the
depth of the intoxication.

Korenevskaya studied the effect of high air temperature on the
processes of accumulation and dissociation of carboxyhemoglobin in the blood
in the presence of small doses of carbon monoxide and the relation between the
rate of carboxyhemoglobin accumulation in the blood and the appearance time
of intoxication symptoms.

Women were noted working in atmospheres of low carbon monoxide
at temperatures of 20° to 25°C (68° to 77°F) and at 40° to 50°C (106° to 122°F).
After working in the hotter environment, women complained of general malaise
and frequent headaches. Later experimental work on rabbits showed that, with a
rise in air temperature, the toxic effect of carbon monoxide increased due to a
complex of causes.

In comparing concentrations of carboxyhemoglobin in the blood with the accompanying symptoms, Korenevskaya found it apparent that in hyperthermia a lack of parallelism existed between carboxyhemoglobin content in the blood and the gravity of intoxication. In isolated cases, the blood carboxyhemoglobin concentrations of individual animals exposed to carbon monoxide and hyperthermia were not higher, and at times were lower, than in cases of similar carbon monoxide exposure at normal air temperatures. Yet, the symptoms were more pronounced. The increased action of carbon monoxide in hyperthermia was disproportionate symptomologically to the concentration of carboxyhemoglobin in the blood, leading to the conclusion that carboxyhemoglobin concentration in the blood in hyperthermia cannot be regarded as the criterion of the gravity of inhaled carbon monoxide toxicity and vice versa. In addition to the intensification of the effect of carbon monoxide in combined hyperthermia and carbon monoxide intoxication, the organism's resistance to temperature was also reduced. Thus, the toxic effects of carbon monoxide in hyperthermy were synergistic, a fact which was expressed in intensified clinical symptomological pictures.

As a part of this project, a limited number of animal tests were conducted. Adult male Swiss albino mice, 25 to 30 grams in weight, were exposed to varying degrees of carbon monoxide in combination with hyperthermia. A significant reduction in the average time of death was noted when heat was applied in conjunction with the carbon monoxide. Figure 21 illustrates reduction in survival times by a factor of 5 to 12.
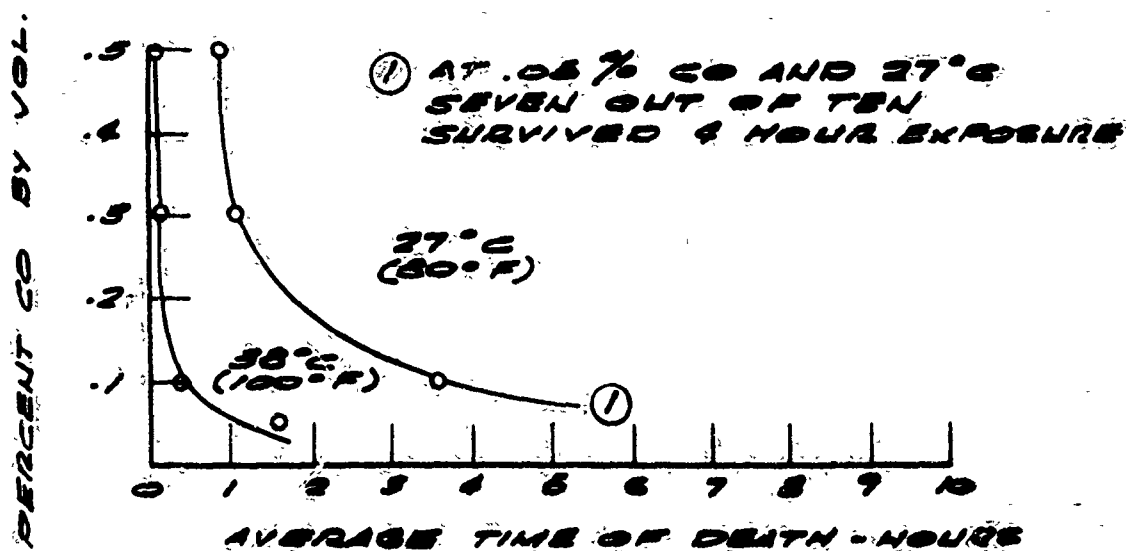
Source: SwRI

FIGURE 21. SYNERGISTIC ACTION OF HEAT AND CARBON DIOXIDE ON WHITE MICE

In addition to the studies performed on the synergistic aspects of the various products of combustion from fires, there has also been a considerable

amount of experimental work accomplished on some of the other synergisms to be expected with the mass fire environment created by a thermonuclear weapon. While the effects of radiation (other than thermal radiation) are outside the scope of this study, it is of interest to note a study of the synergistic action between whole body irradiation and thermal burns. In work by Brooks,[42] dogs were exposed to 25 r with no mortality, and to 100 r with no mortality. Exposed to a deep second degree thermal burn over 20 percent of their body, 13 percent of the dogs died. When exposed to a combination of 25 r and 20 percent body burn, 33 percent of the dogs died. Exposed to a combination of 100 r and 20 percent body burn, 76 percent of the dogs died. This is an increase in mortality by a significant factor of 6.

H. Smoke

Smoke is a distinct and separate hazard from the gases previously mentioned. It consists mainly of carbon particles and other inert materials. Smoke has two potentially hazardous effects: (1) it reduces visibility, and (2) it may be injurious to the lining of the respiratory tract.[385]

Its first effect is obviously psychological, caused by the obscuration of vision. This is evident in reading the accounts of such holocausts as the SS NORONIC, the Cocoanut Grove nightclub, the Iroquois Theater, the Hartford Circus, the Winecoff Hotel, and many others.

In recent years, there has been considerable concern regarding the hazard from smoke as it affects visibility. This is reflected in the manner in which interior building finish materials sometimes are regulated on the basis of smoke developed while burning. ASTM Standard E-84 is the fire test method used to measure smoke production. [8]

In discussing the hazards of smoke, Soland, et al.[318], concluded that ordinary smoke, exclusive of any specific gas, acts as an irritant to the entire respiratory tract causing inflammation. Zapp[386] found that certain pyrolysis products from foamed plastics caused disturbances of the gastro-intestinal tract in his test animals. Levin[184] raised the question of the lungs shutting off the inflow of noxious substances and the automatic swallowing of the poisons. This is refuted by Soland[318] who states that smoke is inhaled. Phillips[270-273] considers the respiratory hazard far more serious and the need for oxygen urgent in addition to the possibility that not only may inhaled gases damage both lung and stomach, but gastric juices, regurgitated by the distressed stomach, may be choked into the airway. Yuill and Bieberdorf[385] stated that the preponderance of opinion appears to be that the initial hazard of smoke is related to visibility and, to a lesser extent, to panic. Late effects of severe exposure appear to be internal trauma and possibly toxemia.

Mallory and Brinkley[199] in reporting on the victims of the Cocoanut Grove disaster felt that the critical injury was the result of some inhaled

irritant, either physical or chemical in nature, and that inhalation of flames could not account for this type of lesion.

Finland[112] reporting on the 131 cases admitted to the Boston City Hospital from the Cocoanut Grove fire suggests the inhalation of the very hot air and fumes, which presumably contained many toxic products and numerous hot particles of fine carbon or similar substances in the smoke as an explanation of the respiratory tract damage. Carbon-like particles were contained in the sputum raised for several days in some of the survivors, and they were mixed with the exudate found in the trachea and in the large and small bronchi of the fatal cases.

Fineberg[111] states that the clinical manifestation of respiratory tract injury may follow noxious gas or smoke inhalation. Davis, et al.[85], concluded that many deaths, which are diagnosed as due to respiratory burns, are more frequently due to pulmonary edema and asphyxia resulting from the inhalation of either smoke or other fumes which have been produced by combustible materials.

Some work has been done and other work is underway to define the relative hazard of smoke emissions from the burning of specific materials. A program conducted at Underwriter's Laboratories Inc., provided basic data on which reasonable smoke limits, as determined by the ASTM E-84 test, could be established but only regarding the hazard of light obscuration.[32]

In short, it appears that smoke, per se, presents a rather poorly defined physiological and psychological hazard in the event of fire. Little qualitative or quantitative work has been done to establish the degree of hazard in individual fires. None of the experimental work done or in progress appears to have any relationship to the mass fire life hazard.

The personal experience of the authors, corroborated in discussions with fire fighters, supports the contention that thick smoke can obscure vision, can cause excessive lachrymation, and can actually be painful when inhaled. Under the stress of mass fires, these effects could be exaggerated and could have an effect on the survival rate.

V. RELATIVE IMPORTANCE OF COMBUSTION PRODUCTS

In addition to recognizing the life hazard as presented by the various parameters found within the mass fire environment, it is important to understand their relationship with each other and the relative importance of each. As previously stated, the mass fire environment is a complex and changing one, dependent on many variables, a few of which are: (1) the composition of fuel or combination of fuels, (2) fuel geometry, (3) ventilation, (4) temperature, and (5) fuel density.

Perhaps the best evidence should be available from the records of actual mass fires such as occurred in Hamburg, Germany (1943); Tokyo, Japan (1923 and 1945); San Francisco, California (1906); Chicago, Illinois (1871); Peshtigo, Wisconsin (1871); and the large forest fire which covered 3,000,000 acres in northeastern Washington, northern Idaho and western Montana in 1910.

Accounts of these fires are largely subjective, and, in some cases, the best the reader can do is to get an overall impression from reading each narrative. These impressions can then be pieced together, and, if a pattern is evident, an opinion can reasonably be developed.

Such an opinion has been formed after reading the accounts of Busch[59], McIlvaine[215], Spencer[320], Morris[234], Kennedy[166], and others that the predominant hazard in the open in a mass fire environment is heat. These narrative accounts contain many references describing the intense heat and the relatively few deaths resulting directly from the fires. Leasor[179] describes the London fire of 1666 and reports four deaths from fire—two persons were trapped, one was overcome by fumes when he reentered a burning building, and one refused to leave his burning home. Conwell reports on the Boston Fire of 1872 and the "many of whom gave their lives" and the "rumors of losses, of dreadful deaths." The deaths when examined closely by Conwell were mostly firemen struck by falling walls or trapped in burning structures.

Reminiscences of Chicago during the Great Fire[215] contain many references to the "intense heat" and "violence" of the wind; however, there are no indications of any deaths occurring among the people rushing about the streets in close proximity to the fires or even among those crowding in the darkness into the cooling water of Lake Michigan.

Cromie[83], reporting on the Chicago fire, cites several incidents where the firemen and citizens braved intense heat in attempts to save property. The wind is reported to have prevented the movement of trained firemen, and the smoke is cited as suffocating in one case. There are no references to any observations of death caused by exposure to gases, smoke, or heat in the streets; however, there are several references to the severe conditions presented by the combination of wind and heat which prevented travel in various

areas of the burning city. The author reports that 120 bodies were recovered, most of which were determined to have succumbed to the fire after having been trapped.

Accounts by Tyler[340], Morris[234], Sutherland[333], and Kennedy[166] of the San Francisco earthquake and fire contain descriptions of death coming to many by fire as a result of their being trapped in collapsed buildings. These accounts are conspicuously free of any references to people dying as a result of exposure to fire gases or heat in the streets.

Busch's[59] account of the Tokyo earthquake and fire of 1923 which killed over 100,000 people offers one of the best documented accounts of a large mass fire. To some degree, the high loss of life—140,000 if the missing are included—may be attributed to the many burned bridges and the large stored quantities of highly combustible goods which served to trap many of the victims. However, the large loss of life is attributed less to these causes than to one special factor. This was a change in the weather that occurred during the fire. The reference here is to whirlwinds or tornados as the author refers to them.

The deaths of nearly 40,000 people who had gathered at the Clothing Depot is described in connection with a whirlwind which was 100 to 200 meters high with a velocity of 70 to 80 meters per sec (160 to 180 mph). Busch states that oxygen is plentiful even during a conflagration and that there is "enough to sustain both the fire and the people—unless both are in the same place, in which case the people usually burn to death anyway. However, in the case of fiery whirlwinds or tornados, this may not hold true. In Tokyo, when a large whirlwind or tornado passed over an area, it often left so much carbon monoxide in its wake that even those who had not burned to death died within a very few minutes from the effects of the poison." Such an incident was described and took place near the Yoshiwara district where 600 died. The bodies were not burned, and it is concluded that a "tornado" passed over the area.

Busch's report includes personal accounts of survivors who lived through the intense heat while others in the immediate area perished. In each of these cases, the survivors were badly burned but could assign their survival to some garment or barrier which protected them from more exposure to the heat.

Spencer[320], reporting on the forest fires of 1910 which burned 3,000,000 acres over northeastern Washington, northern Idaho, and western Montana, cites the personal experiences of a number of survivors. Fire-fighting crews were trapped and cut off from escape in this fast spreading series of fires, and several accounts of survival from those present speak for the conditions encountered. Many of these accounts are from reports of experienced forest fire-fighting personnel. With few exceptions, the major hazard

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appeared to be the heat. There are numerous references to smoke and its nuisance value in stifling breathing. One incident is reported of survival within the fire area in a cave. Forty-five men sought shelter, and many of them "soon became unconscious from the terrible heat, smoke, and fire gas." Five died as a result.

The wind was reported as so strong that it lifted men out of their saddles and pushed the fire along at 20 to 70 mph. There are several reported survivals of fire-fighting crews which suffered heat so intense it "took my breath away." Some were surrounded and literally overrun by the fire. One forest ranger stated "a few yards below a great log jam, an acre or more in extent, became a roaring furnace; a regular threatening hell. If the wind changed, a single blast from this inferno would wipe us out."

Hundreds of these men were badly burned yet were able to survive. Men who went mad tried to escape through the flames and were "burned to death only a few yards from where the rest of the men lay." In one instance, "140 men caught in a valley not 50 yards wide with sides arising about 500 feet on an angle of 45 degrees, and covered with a thick growth of timber, and the bottoms covered with cedar trees that burn almost like tinder" survived when the entire area burned out directly over them without the loss of a single man. Thus, all factors considered, the author gives the impression that heat was the primary hazard. In a few cases where some protection from the heat was available, as in a cave, the smoke and fire gases apparently were sufficient to kill a small percentage of the sheltered.

Kehrl[164] describes the firestorm in Hamburg during World War II and the manner in which death occurred. Many "waited in shelters until the heat and the obvious danger compelled some immediate action. In many cases, they were no longer able to act by themselves. They were already unconscious or dead from carbon monoxide poisoning." Many lost their lives attempting escape through the streets when their clothes caught fire. For some that remained in the shelters, the heat literally destroyed any trace of them as recognizable human beings. People who were attempting escape "fell down, overcome by the devouring force of the heat and died in an instant." Dead were found in the streets "in every posture, quiet and peaceful or cramped, the death struggle shown in the expression on their faces. The shelters showed the same picture." Kehrl cites examinations made which concluded that death of many, particularly those found in a seemingly peaceful state both in shelters and in the streets, was caused by carbon monoxide. Kehrl also describes the violent winds of the firestorm which uprooted and broke off trees a meter in diameter.

Buettner[52] believes that heat radiation and carbon monoxide in the air-raid cellars on the one hand, and mechanical danger and heat radiation in the streets on the other, prevented escape of the people who afterwards were killed. "The victims escaping through the streets were surrounded by relatively cool air, but were still within the radiation area of large conflagrations."

The United States Strategic Bombing Survey (USSBS)[349] concluded that during escape from overheated shelters through burning city blocks, the injuries were chiefly from radiated heat. In addition, Baniecki noted shock as a large factor in causing death to those people caught out in the streets. Shock was noted as the cause of death in 12.6 percent of all patients hospitalized from bombed areas.

The USSBS further concluded that the majority of deaths was due to carbon monoxide poisoning. In Hamburg, Kassel, Darmstadt, and Wuppertal, the estimate of the number so killed was fixed as high as 70 percent of all deaths by those interviewed in the survey. "The greater number of these cases were found in shelters slumped over in the relaxed position which is an outward physical symptom of carbon monoxide poisoning." The strength of evidence for such conclusions obviously came from a large degree as a result of the 20,000 to 30,000 autopsies estimated by Professor Buechner, consultant to the Luftwaffe, to have been performed on air-raid victims. Baniecki[21, 22] reports on the opening of a shelter in Hamburg some thirty hours after the air raid; the intense heat prevented an earlier entrance. Forty-three bodies were found. "They were seated on benches, some leaning back and some forward as if they had fallen asleep. Clothing apparently torn off and lying around led one to suppose that the occupants suffered very severely from the heat." Thirty bodies were examined and three were autopsied. On the basis of chemical blood tests (tannin test, formalin test) which indicated the presence of carbon monoxide, it was concluded that all forty-three occupants of the air-raid shelter died of carbon monoxide poisoning. This possibility, that of carbon monoxide deaths in shelters, seems to be strongly supported by a report of carboxyhemoglobin saturations as high as 95 percent found in many shelter dead.[350]

Thirty-six hours after the raid, twenty-four bodies were examined externally from a shelter at Barmbeck, and five of these were autopsied. A positive reaction to the carbon monoxide in tannin and formalin blood tests was found.

In an attempt to study the causes of death to those persons who died in the streets, Baniecki performed autopsies on four persons. On the basis of results obtained from these autopsies, it was concluded that two died from carbon monoxide and two died from burns.

Baniecki also investigated deaths that occurred in Bremen after a large air raid. These investigations were particularly aimed at identifying the cause of death of those people seen fleeing from their shelters but who died after taking but a few steps in the open. Three bodies from the Bremen raid were autopsied eighteen hours after the start of the raid[22]. Baniecki determined the carboxyhemoglobin content of the three bodies to be 11, 5, and 14 percent. This was concluded to be a sublethal dose of carbon monoxide, and the cause of death was stated as follows: "To sum up, there was found the condition of tissues of the upper breathing tubes and lungs damaged by the

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inhalation of hot air. The interchange of gases prevented by the stasis was aggravated by the oedema of the lungs, by haemolysis and by the consequent interruption of the respiratory epithelium of the lungs. Very soon a condition similar to that of suffocation arose which caused the death of those lying in the street even before the full effects of the heat were felt."

The USSBS[350] states that "High temperatures will destroy carbon monoxide hemoglobin. Putrefaction will not destroy carbon monoxide hemoglobin." This statement further clouds the issue. Perhaps those victims autopsied by Baniecki, who had 11 or 14 percent carboxyhemoglobin in the blood, may have had higher blood saturations which were destroyed by the heat which was determined to be the cause of death. In addition, the tannin and the formalin tests used are only rough qualitative measures and are not quantitative tests[279].

Earp's[98] conclusions are in agreement with Kehrls in that heat and carbon monoxide were the two most frequent causes of death. She states, "In the streets, deaths from heat effects predominated, whereas in the shelters the deaths were mainly due to carbon monoxide." Earp continues, "Various estimates have been made of the proportion of the total deaths due to carbon monoxide poisoning. Such estimates which vary from 80 percent of all deaths (USSBS No. 65, page 28)[351] to 20 to 30 percent (Baniecki, 1950) are little more than informed guesses since the number of autopsies performed was too small for a reliable estimate to be made." Lack of oxygen or an excess of carbon dioxide in the streets is ruled out as a possible cause of death because of the high rate of natural ventilation.

Earp cites Graeff as performing fifty-five autopsies on shelter victims and concluding that death was probably due in thirty-four cases to carbon monoxide poisoning, in five cases to the excessive heat with carbon monoxide poisoning also a possibility, and that in the remaining sixteen cases death might have been due to either or both of these causes. Thus, Graeff concluded that as regards deaths in shelters, carbon monoxide is the dominant factor and that this is followed by heat exhaustion as the most frequent cause of death.

Earp notes that many deaths in the streets were ascribed to carbon monoxide and concludes that many of these deaths were due mainly from receiving a lethal dose of carbon monoxide in the shelter from which they escaped. This uptake of carbon monoxide was then enough to cause collapse when the effort of escape was made. Earp states, "There is no evidence concerning the percentage of carbon monoxide present in the streets, but it seems likely that generally it was present in insufficient quantity to cause death before the victim succumbed to the excessive heat."

Leutz[183] states, "The predominant cause for the majority of fire victims, even in the open areas in firestorm areas is hyperthermia. In only a few exceptional cases does carbon monoxide poisoning come into question."

Also, there is evidence to the effect that many shelters were overcrowded by a factor of 2 or 3; however, no deaths are reported in these instances due to the internal heat or carbon dioxide buildup, even where the ventilation units had to be shut down because they were bringing noxious gases and smoke into the shelter.

Miller and Kerr[223] interviewed Leutz during the course of a visit to Germany in 1965 and Leutz "emphasized (repeatedly) that heat (hyperthermia) effects were the main cause of death in all the mass fires in Germany, and stated that in no individual case could it be established that either lack of oxygen or the presence of carbon dioxide was the cause of death." A minor secondary cause of death, he said, "was the presence of carbon monoxide (i.e., some people were poisoned by the gas)." Dr. Leutz was in Hamburg during the large raid of July 1943. The graph of the firestorm temperature that he estimated is presented in Figure 2.

Miller and Kerr also interviewed Brunswig (Fire Chief of Hamburg) who said that fire was the chief cause of death and destruction, and its effects were much more severe than the blast damage; in the open, the hot air was the major cause of death. In one case, he noted (from a photograph of a group of dead people in the street) that death in the open occurred at a distance of 150 meters from the nearest burning building. As a result of previous preliminary evaluation, Miller concluded that "the major out-of-door hazard to life, in large fires, is the exposure to heat radiation and/or to contact of the skin with the heated air."

In a recent preliminary evaluation of fire hazards from nuclear detonations, Miller[222] lists the major hazards as heat, carbon monoxide and carbon dioxide (plus other toxic gases) and oxygen depletion. "The major out-of-door hazard to life, in large fires, is the exposure to heat radiation and/or to contact of the skin with the heated air. The skin surface burns resulting from such contact are considered to be more important causes of fatalities than is the breathing of hot air." Carbon monoxide is recognized as the "predominating toxic gas produced in fires," and it is suggested that "oxygen depletion in mass fires is not a major cause of casualties." "The major causes of death in sheltered spaces appear to be related to the fact that burning rubble may cover unsealed shelters and the shelter's air intake. The incoming air, drawn past the burning fuel or the remaining coals, contains high concentrations of carbon monoxide, is hot, and is depleted in oxygen."

In a study of the effects of mass fires on personnel in shelters, Broido and McMasters[37] concluded that extreme carbon monoxide concentrations are to be expected and that oxygen depletion and high carbon dioxide concentrations may also occur. The effects of the oxygen and carbon dioxide will be of consequence only if some steps are taken to eliminate the carbon monoxide hazard when it is present in such high concentrations.

Reports by Yuill and Bieberdorf(385), Zapp(386), Dufour(95), Claudy(74), and Easton(99, 100) lean strongly toward carbon monoxide as the primary hazard; however, the contributing effect of a host of other noxious gases and smoke in the presence of heat is recognized as possibly being the cause of a significant synergism resulting in rapid death.

After the presentation of such a list of opinions, a conclusion is in order. It does appear that there is a strong opinion held by most investigators of the mass fire life hazard that the primary hazard to those in the open is heat. Pearse(265) notes that 90 percent of the Japanese who sought aid in the first week after the atomic bombing did so because of thermal burns.
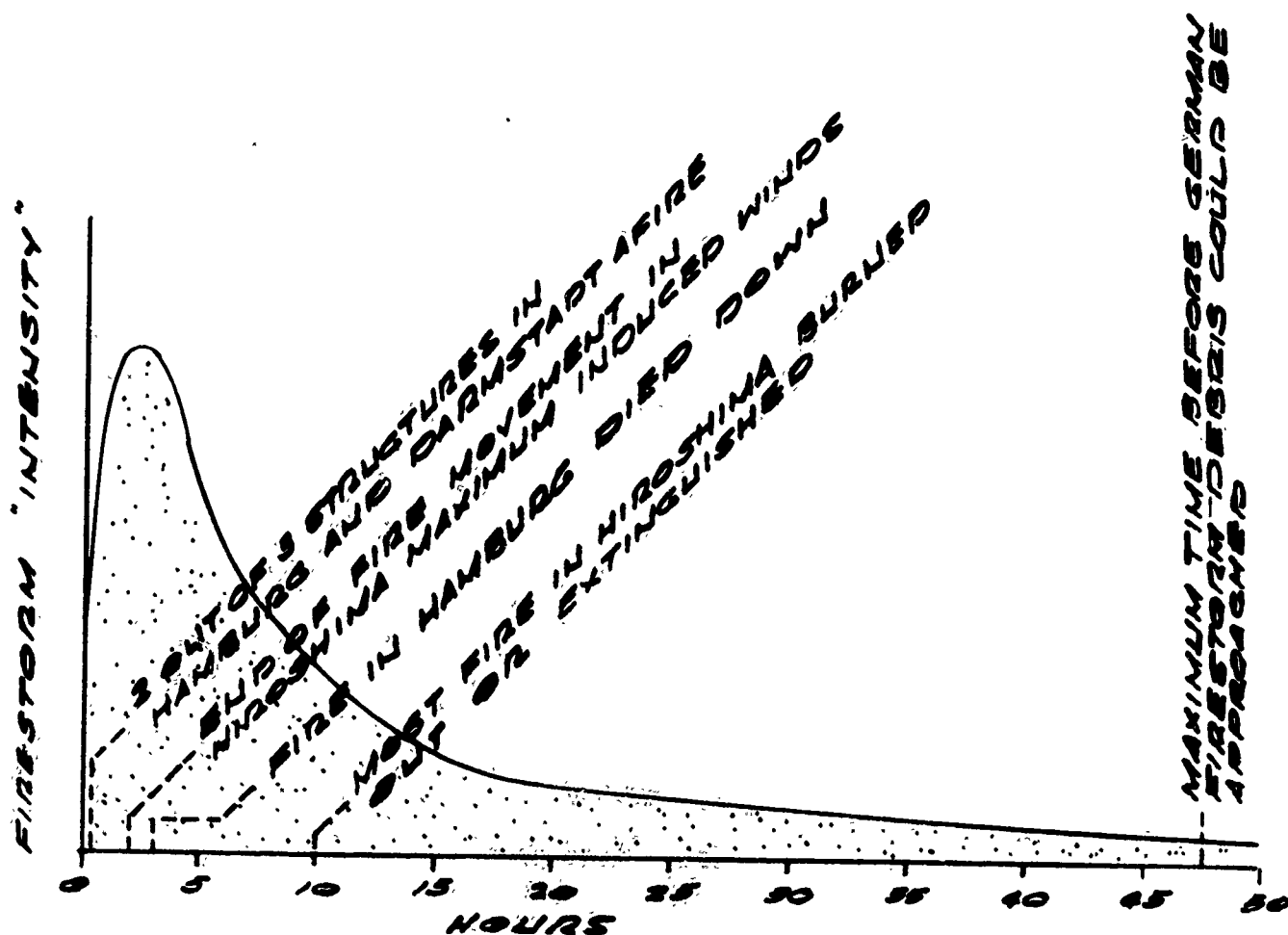
Source: See Ref. (288)

FIGURE 22. QUALITATIVE TIME BEHAVIOR OF FIRESTORMS

Figure 22 is an estimate of a firestorm intensity; a conflagration is, of course, much shorter(242). The fact that other hazards are present and may frequently appear as the primary cause of death is recognized. The combined effect has also been considered; however, the state-of-the-art has been such that definitive relationships are unknown. Gaps in the knowledge of both the effects of

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combinations of heat, noxious gases and smoke and also of brief exposures to high concentrations of each have led past investigators to the conclusion that the most toxic hazard present is the primary cause of death without considering other possibilities.

There also appears to be considerable agreement as to the cause of death in shelters, and this agreement can easily be appreciated when the investigations are examined in terms of the exposure conditions. The chief hazard in unsealed shelters is the exposure to rubble collecting over the exits and ventilation ports causing heat, carbon monoxide, and other fire gases to enter; if the shelter is closed and protected from this rubble, the chief hazard is the exposure to the enduring heat of the mass fire environment which exists around the closed shelter. "Casualties in shelters (from air raids and resulting fires) were principally confined to apartment building shelters where personnel were often trapped by collapse or fire."[98]

The two exceptions to these conclusions are noted by Leutz who disregards the hazard of carbon monoxide and Magnus who states that most of the people who died in the bunkers in a Mannheim raid of 1943 died because of lack of oxygen[223].

There has been considerable interest in the medical profession in defining the exact cause of the deaths ascribed to hyperthermia. While there is general agreement among the investigators on the nature of the physiological response to heat, there is also a deeper searching for a better definition of the cause of death of "hyperthermia."

The Cocoanut Grove disaster is probably the best example of fire deaths offering a puzzle to the medical profession. Two of the principal investigators of this incident, Phillips of the Massachusetts General Hospital and Finland of the Boston City Hospital have recognized respiratory tract injury as the primary cause of death in burned patients. This respiratory tract injury is ascribed by both investigators to the inhalation of the products of combustion. In another study, Phillips[272] reports that 181 patients culled from the records of 932 burned patients were investigated, and, in 150 of these cases, the difficulties are attributed to damage to the respiratory tract resulting from the inhalation of noxious products of incomplete combustion. The importance of this factor as a cause of death in the World War II mass fires is not known and may not have been fully considered.

Several investigators have undertaken experimental studies to determine the relative importance of some of the variables in an attempt to define: (1) those of most importance, and (2) their relation to each other. The work by Zapp[386], previously mentioned, was specifically designed to this end. As a result of this work, Zapp concluded that the most important lethal factors in conflagrations under conditions of poor ventilation are oxygen deficiency, carbon monoxide, and heat, all of which contribute to anoxia. Under conditions of good ventilation, heat would be the dominant factor. Thus, for a given quantity of fuel, the chances for survival would be better under conditions of

good ventilation. Zapp concluded that it did not seem necessary to postulate the presence of other toxic gases such as nitrous fumes, phosgene, hydrogen cyanide, hydrogen sulfide (although these may be present and significant in special circumstances) in order to account for the death of casualties in conflagrations where skin burns are present, or appear to be of minor importance.

Finland[112] comes to a similar conclusion from his studies of the Cocoanut Grove disaster victims by virtue of the fact that there appeared to be no correlation between the location where the persons were found and the amount of respiratory injury sustained. Thus, it was concluded that the respiratory irritant was directly related to the heat and flames of the fire as opposed to any specific irritant independent of the usual products of combustion.

The problem of defining the cause of death in fire victims is well pointed up by the ad hoc panel of the Committee of Pathology of the National Research Council. After studying forty-one autopsies conducted on fire victims, the panel concluded that respiratory tract damage can be and has been overlooked at autopsy as a result of the lack of systematic examination of the entire respiratory tract.[2]

There appear to be two distinctly different life hazard situations in mass fires--one in the open and the other in enclosed spaces. Review of the literature indicates heat as the primary cause of death in the open. While there was not complete agreement, the majority of opinion appears to be that carbon monoxide is the primary cause of death in closed spaces. In each case, the presence of the other factors plus the hazard of noxious gases and smoke is recognized, but their significance has not been established.

There is one further distinction that must be made regarding deaths in closed spaces in World War II, and that is, these deaths occurred only in those spaces which were directly exposed to burning structures, high concentrations of combustion products, and the latent heat from burning or smoldering rubble. In the latter case, heat also is suspected of being the primary cause of death. Medical research indicates that the primary cause of death in burn patients in closed spaces is respiratory tract injury, and this is suspected to be caused by the inhalation of noxious gases, smoke and heat. Carbon monoxide and reduced oxygen have never been recognized as the cause of any alteration in the respiratory mucosa.

The importance of synergistic effects has been recognized, and preliminary tests have shown its significance. A true definition of the mass fire life hazard requires a complete understanding of the combined action of the principal elements in the combustion products from building fires.

Until such time as the exact nature of mass fires (conflagrations, firestorms) is understood or better defined, the nature and effects of the various combinations of combustion products therein can only be conjectured.

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A definition of the mass fire life hazard involves three factors: (1) the mass fire environment, (2) the survival limits of man, and (3) the protective ability of any chosen shelter. In previous sections of this report, the mass fire environment and the life-safety limits of man have been discussed. In this section, the factors affecting survival in mass fires will be considered.

The present OCD program involves the provision of fallout shelters, and, to this end, surveys have been conducted to choose buildings with the necessary protection factor, selecting the areas within these structures to be occupied for periods up to two weeks, and stocking them with the necessary supplies.[254, 255] These shelters are located primarily in the centers of large urban areas. In the event of an attack, it is obvious that many people will be forced to seek refuge wherever possible. Some will be in designated shelters, both above and below ground. Others will be in homes, basements, vehicles, commercial buildings, apartment buildings, public buildings, subways, and some may be caught in the open.

With the information known to date, it is impossible to predict the mass fire life hazard in any one of these situations other than to foresee high mortality in some structures which are completely burned out and relative safety in others. Nevertheless, this discussion is still worthwhile if for no other reason than to recognize the types of situations that may be anticipated. Some of these are as follows:

Conflagration - No Fallout. There have been many peacetime conflagrations in history, and a brief review of these reveals that life safety is periled but not seriously endangered. Chandler, et al.[68, 69], reporting on fire spread in urban conflagrations estimated their speed at from 0.014 mph to 4.536 mph. The average speed of twenty-two reported fires was 0.134 mph. Such fires cause a great deal of confusion ahead of them; however, there does not appear to be any great difficulty in escaping their path. The loss of life in conflagrations has occurred in those instances where people have been trapped by: (1) falling debris as in an earthquake, or (2) encircling fires which have sprung up from a number of separate ignitions such as in large forest fires set by lightning strikes over a large area.

It is noteworthy that conflagrations have occurred which burned their way through populated areas without the loss of a single life. The Los Angeles fire of 1961, which burned its way through 513 homes and 24 buildings, covered an area of 6090 acres and had a perimeter of 19.6 miles. No one was killed.[374] In 1923, a grass fire swept into Berkeley, California and burned 640 buildings over an area of 130 acres without the loss of a single life.[239] These fires are not expected to be typical of those to be encountered in war. The fires

started by either a thermonuclear weapon or incendiary bombs will be numerous, and, if a single mass fire approaching or equaling a firestorm is not developed, a series of conflagrations may be expected. Such a fire would then threaten the populace by cutting off escape routes much the same as in the Tokyo fire of 1923[59] or the San Francisco fire of 1906.[166, 234, 333, 340]

The loss of life under such circumstances would depend greatly upon the people's actions. If escape were attempted, some deaths probably would occur in the open if people become trapped between fires. If the populace took shelter and made no attempt to escape, the survival rate would depend largely upon the adequacy of the shelters. The majority of people in Hamburg did not seek escape because: (1) they had confidence in their fire-fighting forces who had successfully controlled the fires from previous raids, and (2) the constant stream of high explosive bombs kept them under cover.[223]

Where the building density is 40 to 60 percent and higher, the loss of life is expected to be high.[38, 183] The separation distances will be smaller, and the outside exposure conditions of heat, carbon monoxide, smoke and noxious gases would be more severe.

Conflagration - Fallout. The fear of fallout would tend to inhibit those wanting to escape through the streets and thus increase the population of shelters. In the case of a conflagration with fallout, some will be in shelters attempting to wait it out, and some may still attempt to escape or perhaps seek a different shelter area. Those that seek shelter and stay there again will survive in direct relation to the shelter's capacity to protect from the mass fire environment. In this case, the nature of the fire may not be of much concern, for whether it is a conflagration or a firestorm may be academic, i.e., being in the middle of either one may be essentially the same.

Firestorm - No Fallout. Where a firestorm develops with no fallout, the populace is in much the same situation as those in Hamburg. If escape is elected, the success depends on the distance to the edge of the firestorm, speed of the escapee, and the rate of development of the firestorm. If shelter is chosen, then the situation is similar to the conflagration; i.e., survival now depends on the shelter's ability to protect the occupants from the mass fire environment.

Firestorm - Fallout. In this case, the population, if warned and knowledgeable, will attempt to seek permanent shelter for the duration of the fire and unsafe period of fallout. If the weapon is exploded at low altitude so that the fireball does touch the earth, the fallout may not arrive immediately, thus allowing escape from the firestorm area. Once escape from the firestorm area is accomplished, protection from the fallout must then be found for those in its path.

In each of the situations listed in the previous paragraphs, people will be seeking shelter in all types of structures, and each must be considered for its capabilities in each of the situations. A review of designated and stocked shelters by Varley and Maatman[357] indicates that fire-resistive construction is prevalent, not all floor openings are protected, average occupancy is of a commercial or public nature, most designated and stocked shelters are below ground, and most of the sheltered population will by necessity be in above-ground areas. Considering these shelters in terms of fire vulnerability, it was found that each could be considered in terms of the following:

"1.   Fire would be contained within the floor of origin in fire resistive structures in several occupancy groupings. Schools, churches, offices, banks, residentials, and telephone exchanges would resist fire spread either when a good degree of subdivision exists within each floor, or when all floor to floor openings are protected. Manufacturing buildings with low combustible loading (1-3 pounds per square foot), and those with moderate loading having protected floor openings would also resist the spread of fire.

"2.   Well-subdivided structures capable of preventing fire spread away from the floor of origin would require only minimum efforts by occupants to prevent smoke and toxic gases from reaching dangerous levels. When such structural characteristics are lacking, special equipment and materials must be employed by occupants to effectively minimize the spread of smoke and toxic gases.

"3.   Approximately two-thirds of the surveyed buildings in 'downtown' areas and one-third of those in exclusively residential areas were exposed to ignition from nearby burning structures. Approximately one-half of all buildings exposed to ignition from adjacent buildings could be exposed on more than one side.

"4.   With few exceptions, fire suppression by shelter occupants could be effectively accomplished with sufficient portable extinguishers. Properly supplied standpipe and hose or automatic sprinkler systems will control fire in those exceptional occupancies where rapid fire buildup is characteristic, or where access to combustibles is prevented by considerable bulk storage or concealed combustible building construction.

"5.   The contribution of shelter stock to the peacetime fire severity of shelter buildings is significant only when storage of the combustible portion of these supplies exceeds 100 square feet of floor area and when the normal-occupancy fire loading is relatively light. Such conditions occur when stocks for large shelter

areas located on several above-ground floors are stored in one location. In most cases, combustible shelter supplies will occupy less than 100 square feet when the shelter area and its supplies are located on the same floor."

The fire suppression efforts by self-help teams were developed in a previous report by Vodvarka and Waterman.[361] In this analysis, the authors concluded that an ignition in the shelter building could be satisfactorily controlled through containment of fire in a portion of the building by means of structural fire resistance or through rapid discovery and extinguishment by shelter occupants. This reliance on fire extinguishment will, it is said[357], give favorable results when occupants are adequately organized, equipped, and trained for fire fighting and where these activities are not curtailed by nuclear radiation. The order of preference is given below using shelter building categories developed in the previous analyses by Vodvarka and Waterman[361]:

(1a)   Fire Limiting - No combustibles outside shelter areas.

(1b)   Fire Limiting - Fire gases controllable without special means.

(1c)   Fire Limiting - Fire gases controlled with special means.

(2)   Suppression Dependent

(3a)   Untenable - Fire not controllable with portable extinguishers.

(3b)   Untenable - Problem other than extinguishment.

Further definition of these categories is as follows:

(1)   Fire Limiting

Fire limiting buildings are those in which fully developed fires originating outside shelter floors will not progress to the shelter. The analysis indicates that shelter buildings resisting the spread of direct fires would mainly include those used as schools, churches, offices, banks, residential types, telephone exchanges, and manufacturers with low combustible contents loading. A method for selection of fire limiting buildings is presented by the authors.

As the resistance to direct spread of fire does not preclude possible spread of smoke and toxic gases, this characteristic of fire limiting buildings must be determined separately.

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(2) Suppression Dependent

This intermediate fire vulnerability level denotes those instances
where fire spread cannot be adequately resisted by the building,
but it is possible to extinguish incipient fires using portable
extinguishers. This level includes all buildings not specifically
falling in either of the other two categories [(1) and (3)].

(3) Untenable

This fire vulnerability level consists of buildings where extin-
guishment of fire using portable equipment is considered
unfeasible due to excessively rapid fire buildup, or concealed
or inaccessible combustibles. Identification of buildings having
these characteristics can be made from the following illustra-
tive situations:

(a) Buildings where explosive vapors or dusts may be present,
such as automobile garages and certain types of industrial
occupancies.

(b) Buildings with significant accumulations of wood scraps,
paper, and textiles.

(c) Buildings having combustible stock piles and/or without
adequate aisle space between adjacent piles.

(d) All buildings of masonry and wood frame constructions,
as in these structures concealed and inaccessible combusti-
ble predominate.[361]

1. Self-Help and Shelter Integrity

The effectiveness of self-help fire suppression efforts is seriously
questioned by Degenkolb[87] who believes that in the event of a nuclear attack
where blast and fire are factors, shelterees would not be able to move through
the buildings in time to control or extinguish all incipient fires before it
became necessary for them to return to the shelter to avoid radioactive fall-
out. Degenkolb also contends "that there are practically no buildings of the
'fire-limiting type.' Present day building construction, with its extensive
use of glass, inadequate protection of vertical shafts, dependence on sprink-
lers (which would no longer be operable), and the combustibility of contents,
makes the possibility of any established fire being confined to the floor of
origin quite remote."

Many examples could be cited of peacetime building fires where
an entire floor of a fire-resistive building has been gutted without serious
damage to adjoining floors. Whether nonprofessional fire-fighters with first

aid equipment would be equally successful is a moot point. The lesser damage by fire in Berlin than in Hamburg is attributed by Bond[30] to better fire separations. If burning rubble is a factor, it must be remembered that fire separations in fire-resistive buildings are for from 1 to 4 hr only.

Other examples could be cited of fires spreading through inadequately protected vertical openings and from floor to floor by way of outside windows in fire-resistive buildings.[12, 220, 246]

Generally speaking, the fire-resistive structures with good fire divisions, fire doors, and protected vertical openings are expected to provide a considerable amount of protection. The degree of this protection may be directly related to the density of ignitions throughout the structure and the density of fuel in relation to shelter location.

2. Typical Designated Shelters

An inspection of designated civil defense shelters in buildings in one city indicated that many of these structures are not of the best fire-resistive type; i.e., many are of noncombustible construction but do not have interior cutoffs, fire doors, low fire loading, protected vertical openings, and other such features that exist in a well designed fire-resistive building. The shelter areas, it should be noted, are chosen primarily for fallout protection rather than for protection from mass fire.[255, 256, 258]

a. Internal Exposure to Combustion Products

Within these structures, it is not necessary to have a raging fire to menace the shelterees. The production of smoke, noxious gases or heat elsewhere in the structure may place their life in jeopardy. Operation School Burning, conducted by the Los Angeles Fire Department;[195, 196] tests on smoke invasion by Fackler;[108] and reports of the Cleveland Clinic and Hartford Hospital Fires[161] bear witness to the effects of the travel of combustion products throughout a building.

Experimental fires by Bruce[46] developed internal building pressures of 0.03 in. of water. Countryman[82] found positive pressures in the center of three fires and concluded from his data that the increase in pressure might be greater than 0.05 in. of mercury. These pressures developed by the fire itself are capable of forcing the combustion products into areas of the building remote from the fire.

Likewise, it would appear that maintenance of a positive pressure within the shelter area might effectively keep out the noxious fumes. Preliminary experimental work would appear to support this theory.[313]

The heat released by a comparatively small fire in a shelter may be a serious factor. Johnson and Ramskill[159] have calculated the temperature rise in a 6500-cu ft shelter due to the heat release from a small fire. Their data are shown in Table 17.

TABLE 17. HEAT RELEASE FROM A SMALL FIRE
IN A 6500-CU FT SHELTER

Fuel Consumed, gm		Heat Released, K Cal	Adiabatic Temperature Rise, °C
Cellulose	Hydrocarbon		
460	230	2300	42
920	460	4600	84
1840	920	9200	168

These calculations assume no heat loss to the walls or equipment, nevertheless they must be considered carefully in regard to the life-safety hazard presented.

b.   External Exposure to Combustion Products

In addition to the hazard from combustion products generated within a burning building, there also exists the hazard of combustion products entering a building from the outside; i.e., through open or broken windows, doors, ventilator shafts, or air-conditioning ducts. This situation poses the greatest threat to those areas in buildings on the above-ground floors which are exposed to the mass fire environment through plain glass windows. Many of these areas have even been designated as shelters by OCD on a square footage basis (i.e., 10 sq ft/person). Adequate ventilation is said to be provided by opening the windows.

These areas will be subjected to overpressures from a nuclear weapon, and the glass may be broken. Occupants of these areas will then be exposed to firebrands, heat, smoke and noxious gases. Upward spread of fire from lower floors might produce the same results.

3.   Nondesignated Shelters

In the present situation, it is obvious that the designated shelter spaces are not adequate to protect the surrounding population from other than fallout (which is their prime function), and many will seek shelter in all types of buildings. The majority of these structures will be of the suppression dependent and untenable type. In this case, the shelterees will be exposed to all the hazards previously mentioned in addition to those that such structures present. It is doubtful that such structures will provide any reasonable

degree of protection to shelterees in the midst of a mass fire environment. The only possibility for safety would be in an area of such a building where the construction would provide a vault or a fire-resistive section within which protection from the fire would be afforded. In such a case, smoldering debris would be of major concern where it might block an exit, cut off ventilation, or cause an increase in temperature within the shelter.

B. German Shelter Experience

It is estimated that about 40, 000 of the 280, 000 people in the Hamburg firestorm area were killed.[98] Considering the violence of a mass fire, it is remarkable that some 240, 000 people survived a hazard which was never expected or even realized by most people.

There were four main types of shelters in Hamburg described as bunkers, splinterproof shelters, public cellar shelters, and private basement shelters. Survival in the bunkers and splinterproof shelters was high; in fact, Earp reports that all those sheltered in these types were unharmed (the U. S. Strategic Bombing Survey Reports[349, 352] and the Hamburg Police President's Report[164, 165] are cited as evidence).

Regarding the basement shelters, both private and public, Earp states:

"No estimate is made in the various reports of the proportion of people who survived the raids in these shelters and were able to get out by their own efforts when the raids ceased. On reading the descriptions, perhaps somewhat highly coloured, of conditions in these shelters one is left with the impression of a very high proportion of casualties. However, since it is estimated ... that there were in the Hamburg fire-storm area some 227, 000 people in communal or private cellar shelters of whom about 40, 000 were killed, over 80 percent of the cellar shelterees must have been saved either through remaining in the shelters throughout the raid or by escaping to some safer place while there was yet time."[98]

The U. S. Strategic Bombing Survey[351] states:

"Casualties in shelters (from air raids and resulting fires) were principally confined to apartment building shelters where personnel were often trapped by collapse or fire."

This agrees with Earp's statement and indicates that the majority of deaths in Hamburg occurred in basement shelters under buildings which burned and collapsed.

Appendix 19 of the Police President's Report[165] contains brief information on thirty-three shelters in the Hamburg area. The appendix

contains a description of each shelter and the fate of those who took shelter within. Nineteen of these shelters were identifiable by the present authors and have been plotted on a map of the Hamburg firestorm areas for the purpose of discussion. See Table 18 and Figure 23.

Of the nineteen shelters plotted, nine (possibly eleven) are within the firestorm area reported by Bond[30], five are within the area reported by the USSBS[351], and three are in the firestorm area reported by the Police President Kehrl[164]. Deaths are reported in nine of the thirty-three shelters; in six cases, the cause is concrete loosened by concussion or the direct hit of a high explosive bomb; and, in three cases, the cause of death is reported as the result of fire. Seven of these nine shelters have been plotted, and it should be noted that all three shelters with fire deaths (Nos. 9, 10, and 11) are definitely not located within the fire zones (those marked by a ▲ could not be located precisely, although they are on the correct street). It is possible that the three shelters with fire deaths could all be located within the fire-storm areas reported by both Bond and the USSBS, for there is an overlap which could possibly satisfy the adresses of all three shelters. Two of the six shelters reported as having deaths due to falling concrete (Nos. 24 and 28) are located within the area noted by both Bond and USSBS and are reported as having two occupants killed in one and three in the other. Shelter No. 20, also one of the six reported as having deaths due to falling concrete, is located within an area noted by both Bond and the Police President Kehrl as a fire-storm area. Three shelters reported by both references in the firestorm area had no deaths or injuries (Nos. 12, 19 and 26).

Of the reported shelters, ten are classed as splinterproof types, seven as bunkers, six as private, and nine as public shelters. The fire deaths all occurred in public shelters. This loosely agrees with Earp's con-clusions that no fire deaths occurred in bunkers or splinterproof shelters. The fact that no deaths are reported by fire in nine of the twelve shelters in the firestorm areas reported by Bond, USSBS, and Police President Kehrl is evidence of the survival possibilities.

Appendix 19 of the Hamburg Police President's Report[165] cites several shelter incidents where fire bombs completely destroyed a building directly over a shelter and the occupants were safely protected. Such cases are reported in private shelters as well as bunkers (see Table 18).

It has been estimated[98] that the survival of 240,000 people (out of 280,000 estimated to be present) in the Hamburg firestorm area "might be accounted for as follows (see also discussion on page 109):

Rescued by Police, Medical, Rescue and Armed Forces	30,000
Rescued by Fire and Decontamination Services	15,000
Survived in nonbasement shelters (100 percent of occupants)	53,000
Survived in basement shelters or escaped by their own initiative	142,000
	240,000"

TABLE 18. SHELTERS LOCATED WITH... V

Shelter Number	In Firestorm Area			Deaths/Occupants[165]		
	Bond[30]	USSBS[346]	Kehrl[164]	Fire	Falling Concrete	onc
Private Air-Raid Shelters						
1				0	0	0
2				0	0	0
3				0	0	0
4				0	0	
Public Air-Raid Shelters						
5				0	0	
6				0	0	
7				0	0	
8				0	0	
9	?	?		15/65	0	
10	?	?		67/97	0	
11	X	?		23/53	0	
12	X	X		0	0	
Special Underground Splinterproof Buildings						
17	X			0	1/52	52
18	X		X	0	0	
19	X	X		0	0	
20	X		X	0	12/150	150
21			X	0	0	
22				0	0	
Special Partially Underground Splinterproof Buildings						
23				0	1/300	300
24	X	X		0	3/3	
Special Aboveground Splinterproof Buildings						
25				0	23/35	35
26	X	X		0	0	
Bombproof Surface Shelters						
27				0	0	
28	X	X		0	2	
Reinforced Concrete Shelters						
29				0	0	
30				0	0	

Comments(165)

All occupants safe. Buildings completely destroyed by fire.
Seven safe. House blown away by air mine.
All safe. House demolished and burned out.
Twenty-eight safe. Complete collapse of house.

One hundred twenty-five occupants survived. Severe fire damage.
House burned out and collapsed. All 40 escaped safely via concrete reinforced exit.
House burned out and collapsed. All 140 rescued (not plotted in Fig. 23).
All 15 rescued.
When fire started, 40 to 50 left shelter; remaining 15 were killed. Shelter held.
When fire started, 30 left; remaining 67 died from asphyxiation or smoke. Shelter held.
When fire started, 30 left; remaining 23 died from asphyxiation.
The 650-capacity shelter withstood 3 explosive bombs 40 meters away. The 75-cm
   masonry reinforcements showed extensive splinter damage. Shelter undamaged.
   All occupants exited safely.

One person killed by falling concrete; the other 51 in the shelter were unharmed.
One of two entrance structure roofs torn off; gas sluice doors bent inward. No persons
   injured.
Entrance constructed of masonry sidewalls and concrete ceiling fell over; outer gas sluice
   door bent inward, but exit remained useable. No persons injured.
Building received direct hit; gas sluice door bent outward. Twelve of the 150 occupants
   were killed by falling concrete.
Entrance structure of masonry and concrete fell over, blocking exit. No persons
   injured.
Negligible damage, no injuries.

One exit completely destroyed; otherwise, structure intact. One person killed in sluice,
   remaining 300 unharmed.
Direct hit; damaged beyond repair. All 3 occupants were killed by concrete debris.

Direct hit; damaged beyond repair; concrete-density unsatisfactory. Twenty-three of 35
   occupants killed by concrete (not plotted in Fig. 23).
Direct hit; minor damage to walls. None of the 475 occupants were injured.

Near hit; one person injured in the back. No other injuries sustained.
Direct hit around 7th story, extensive damage; two persons killed by concrete debris.

Outer walls damaged, occupants uninjured.
Near hits; outer walls penetrated by splinters; occupants uninjured.

LEGEND:

FIRESTORM AREA
NOTED BY TOTAL
HOUSE/AREA DESTRUCTION

ILLUSTRATED BURNING
SEVERAL SITES

ENTIRE FIRE INTO THE
TIME AREA

SHELTER:

DEFINITELY LOCATED

APPROXIMATELY
LOCATED

Source: See Refs. (30, 164, 346)

FIGURE 23.   SHELTERS IN HAMBURG FIRESTORM AREAS

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C. Interest in Closed Shelters

Since World War II, the experiences of the Germans and their survival through several firestorms have interested many in the area of civil defense. These investigators have unanimously concluded that survival is possible within the center of a firestorm area if a few simple requirements are met. Broido and McMasters[37], Leutz[181, 183], Marshall[208], Hill[152], Martin and Latham[206], Strope[328-331], Strope and Christian[332], and Schunk[309] generally conclude that a simple underground shelter with the proper protection against heat, smoke, and the gaseous products of combustion is the solution.

Such a shelter presents a serious ventilation problem in that the internal effective temperature, carbon dioxide, and oxygen levels must be maintained within limits. These limits, previously discussed in Section V, are subject to some disagreement between experts; nevertheless, there are obviously limits which must not be exceeded for the safety of the occupants. The closed shelter, therefore, must protect its occupants against two hazards: one is the external mass fire environment, and the other is the internally produced hazards of heat and the carbon dioxide and oxygen balance.

1. Internal Hazard

The relative importance of each factor (heat, carbon dioxide and oxygen) is determined by the human body and its production rate of and tolerance to each. The time factor is determined by the shelter size (volume, surface area), number of occupants, and existing ventilation conditions; i.e., the more occupants in a shelter of given size, surface area, and ventilation conditions, the quicker the buildup of heat, carbon dioxide and reduction in oxygen. Each of these can and does vary in individuals performing different tasks such as sitting, sleeping, and doing heavy work. The following table was prepared by ASHRAE and is one of many on the subject.

TABLE 19. ENERGY EXPENDITURE, OXYGEN CONSUMPTION, CARBON DIOXIDE PRODUCTION AND RATE OF BREATHING IN MAN

Physical Activity	Energy Expenditure, Btu/hr	Oxygen Consumption, cu ft/hr	Carbon Dioxide Production, cu ft/hr	Rate of Breathing, cu ft/hr
Prone, at rest	300	0.60	0.50	15
Seated, sedentary	400	0.80	0.67	20
Standing, strolling	600	1.20	1.00	30
Walking, 3 mph	1000	2.00	1.67	50
Heavy work	1500	3.00	2.50	75

Source: See Reference (7).

The individual human load placed on the closed shelter is:

Oxygen Consumption   0.85 cu ft/hr[328]
Carbon Dioxide Production   0.70 cu ft/hr[328]
Individual Heat Production   518   Btu/hr[329, 330]

It can be seen that the values chosen are between the seated and standing values reported by ASHRAE. Using the chosen values, the relative hazard of each parameter can be determined with regard to time in any particular shelter situation.

a.   Carbon Dioxide Production

Figure 24 represents the production of carbon dioxide in a closed shelter based on the air space (in cubic feet) available per person within that shelter. The volume per person used as a standard by OCD is 65 cu ft/person in shelters with adequate ventilation and 500 cu ft/person in shelters without ventilation. From Figure 24, it can be seen that the limit of 3 percent carbon dioxide will be reached in 21.45 hr, and 5 percent carbon dioxide will be reached in 35.75 hr at 500 cu ft/person assuming a constant production of 0.7 cu ft of carbon dioxide per person per hour.
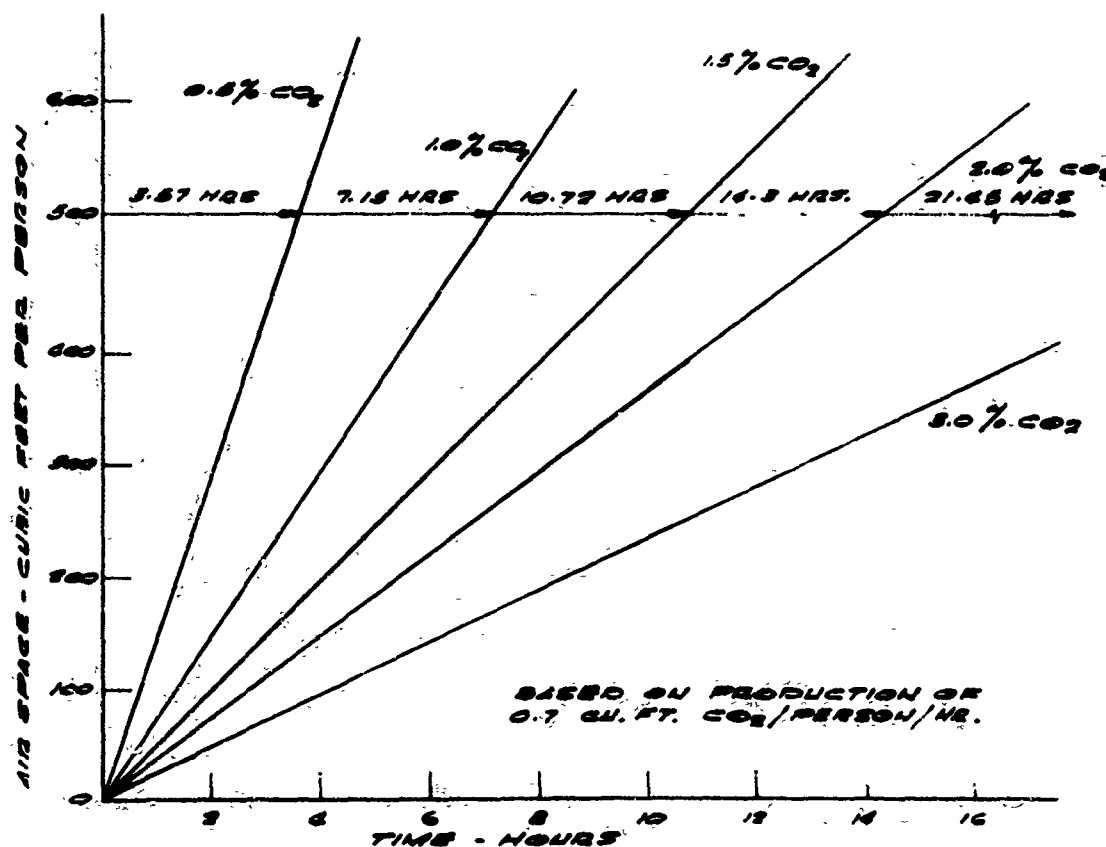
Source: SwRI

FIGURE 24.   CARBON DIOXIDE CONCENTRATION
IN UNVENTILATED SPACES

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The length of stay in the shelter during a mass fire may depend on one of two things or a combination of both—(1) the fire itself, and (2) fallout. For the purpose of discussion, stays for various periods of time can be considered. For example:

Condition	Length of Shelter Stay
Mass Fire - Not Trapped	4-8 hr
Mass Fire - Trapped (await rescue)	24-72 hr
Mass Fire - Fallout	14 days

Based solely on the carbon dioxide content of the shelter as indicated in Table 20, survival appears possible in shelters of the 65 cu ft/person type for 4 hr, shelters of 150-200 cu ft/person are adequate. In any long term stay of 24 hr or longer, only the larger shelters providing 500 cu ft/person or more appear to be safe unless fresh air can be provided in some way to relieve the carbon dioxide buildup. For a long term

TABLE 20. CARBON DIOXIDE BUILDUP IN
CLOSED SHELTER (% BY VOL)

Length of Shelter Stay	Air Space (cu ft/Person)						
	500	400	300	200	100	65	50
4 hr	0.56*	0.70	0.93	1.4	2.8	4.3	5.6
8 hr	1.12	1.40	1.86	2.8	5.6	8.6	11.2
24 hr	3.36	4.20	5.58	8.4	16.8	25.8	33.3
72 hr	10.08	12.60	16.74	25.2	--	--	--
14 days	--	--	--	--	--	--	--

*% CO_2 by volume

stay under conditions of fallout, relief is absolutely necessary. The carbon dioxide concentrations in each case could be reduced by mechanical ventilation or removal in order to extend the safe occupancy period. It might be possible after a 4-hr closure period to draw fresh air into the shelter through a vent protected from debris, excessive heat, smoke, and noxious gases.

The data utilized in this discussion are based on a constant rate of carbon dioxide production per person throughout the shelter stay. Any heat buildup within the shelter will cause an increase in the respiratory volume and heart rate.[25, 26] The oxygen concentration in the shelter area will begin to drop and this also effects an increase in the respiratory volume.[149] In addition, the buildup of carbon dioxide in the shelter continues. Under these circumstances, the respiratory volume can be expected to rise quite rapidly. However, the rate of carbon dioxide production can be expected to drop.

Experiments by Hastings, et al.[143], confirm this fact. Men in a supine position were monitored for the carbon dioxide content of their expired air while exposed to 1.5 percent carbon dioxide in air. An original excretion rate of approximately 190cc/min dropped to approximately 140cc/min after eight days of exposure and then rose gradually over the next five weeks never regaining the original level.[143]

The initial drop in the respiratory gas exchange ratio was explained. Breathing gas containing increased CO_2 concentrations will result in a degree of uptake of excess CO_2 by body alkali in an endeavor to maintain a constant pH. Until a new equilibrium is reached between the increased CO_2 and the CO_2 content of the body buffers, the amount of the CO_2 in the expired air must be less than the sum of CO_2 normally expired by breathing air and the CO_2 added in the experiments.[143]

The combined effect of heat, anoxia and carbon dioxide on the respiratory volume and the carbon dioxide content of the expired air under such circumstances is not known. In a sealed and unventilated shelter, these three factors will be of serious concern and can be expected to increase the hazard, the precise degree of which is not known.

b.   Oxygen Consumption

Figure 25 represents the oxygen reduction in terms of time (hr) versus the air space (in cu ft) available per person within the shelter.
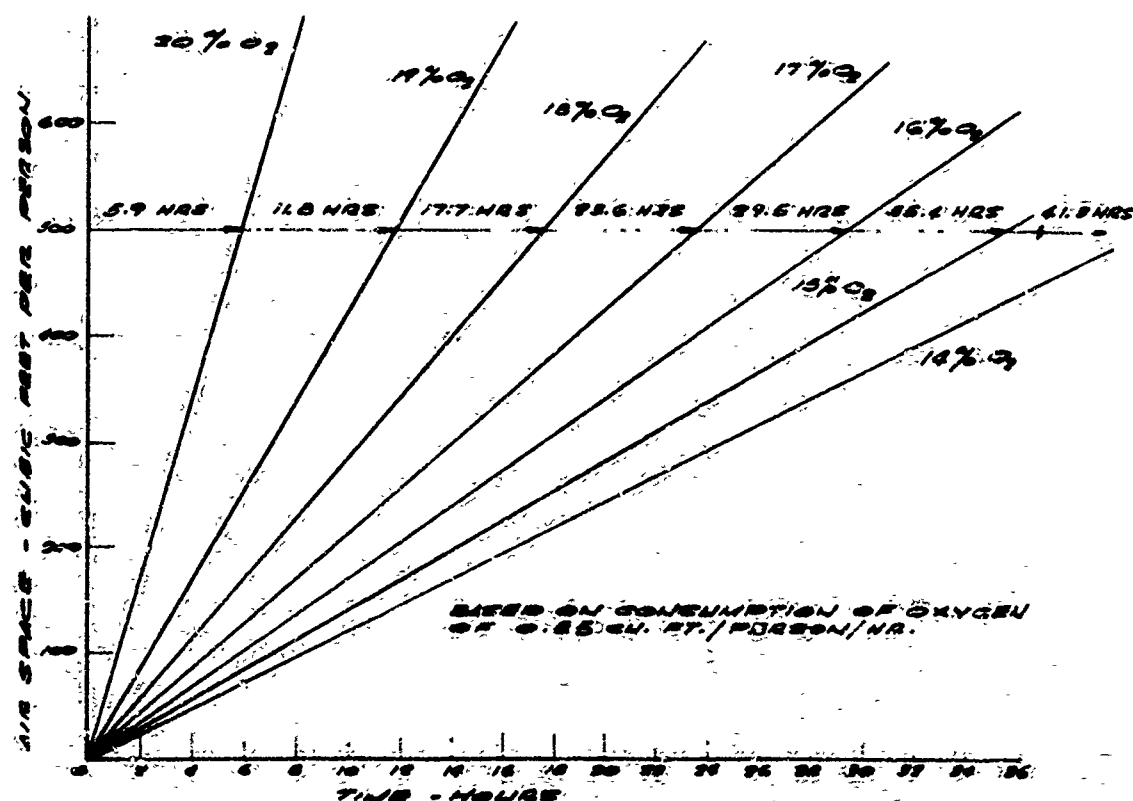
Source: SwRI

FIGURE 25.   OXYGEN DEPLETION IN UNVENTILATED SPACES

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At the OCD standard of 500 cu ft/person, the lower limit of 14 percent oxygen is reached in 41.3 hr, and, at 65 cu ft/person, the limit is reached in 5.35 hours.

This simple comparison is used to point up the fact that the production of carbon dioxide is the determining factor for ventilation when compared with the reduction of oxygen.

c.   Ventilation for Oxygen and Carbon Dioxide Limits

In a fallout situation where a shelter stay of as long as 14 days may be necessary, both oxygen and carbon dioxide can be kept within survival limits by moderate airflows of 0 to 5 cfm/person or higher. Table 21 represents the airflow required to maintain the necessary oxygen content and carbon dioxide level.[7]

The values in Table 21 are valid only where the ventilation is properly arranged to reach all areas of a shelter and actually create the number of air changes it is designed to accomplish. From this table, it can be seen that an airflow of 0.50 cfm per person is sufficient to stay within the 3 percent carbon dioxide and 14-percent oxygen limits. An airflow of 3 cfm is recommended by OCD[204] and is sufficient to maintain the carbon dioxide level at or below 0.47 percent and the oxygen at or above 19.79 percent.

TABLE 21. TERMINAL VALUES OF GAS CONCENTRATION*

Rate of Ventilation, cfm/Person	Terminal Concentration, % by Vol	
	Carbon Dioxide	Oxygen
0.25	5.35	14.13
0.50	2.67	17.23
1.00	1.35	18.77
2.00	0.69	19.53
3.00	0.47	19.79
5.00	0.29	20.11

*This chart is based on an oxygen consumption of 0.90 cu ft/hr/person and a carbon dioxide production of 0.75 cu ft/hr/person.

Source: See Reference (7).

d.   Heat Production

The closed shelter suffers from an additional internal hazard and that is the production of heat by the occupants. Estimated at 518 Btu/hr/person, this heat is sufficient in some cases to raise the temperature within the shelter above bearable limits.

Of this 518 Btu, about 45 percent is given off in the form of latent heat (moisture, at a room temperature of 80° to 85° F). The balance is given off as sensible heat to the surroundings. Thus, the sensible heat so released acts to increase the temperature of the air inside the shelter while the latent heat released acts to increase the humidity.[204] The heat rise in the shelter is dependent on many variables including shelter size, number of occupants within, shelter surface area, heat loss through the shelter, climatic and soil conditions, ventilation, and humidity. This particular phase has probably received more study than any other regarding survival limits within a shelter.

There are two internal heat conditions which must be considered for the closed shelter: (1) the situation where the shelter is closed tightly, and the internal heat production must be absorbed by the walls, floor, furnishings and enclosed air; and (2) the situation where air for ventilation is circulated through the shelter from the outside and might bring in additional heat. Review of previously referenced reports indicates agreement on the point that the rate of air replacement necessary to maintain a safe temperature level in a closed shelter exceeds the rate necessary to maintain proper carbon dioxide and oxygen levels.

Diurnal variations and average outside air temperatures vary throughout the country. The 1964 ASHRAE Guide and Data Book[7], Chapter 30, lists the results of analog computer studies on the rise in temperature after ten days in shelters. In many cases, ventilation rates of 12 cfm/person were unable to maintain the 85° F limit. In several areas, increasing the ventilation beyond a certain rate tended to increase the shelter space temperature, because the outside air was warmer than the shelter walls. Martin and Latham[206] note that the ventilation requirements can easily go well beyond even 12 cfm/person as indicated in Table 22.

TABLE 22. VENTILATION REQUIRED FOR
TEMPERATURE CONTROL[206]

Temperature of Incoming Air, °F	Average Temperature in the Shelter, °F	Amount of Fresh Air Required per Adult, cfm
40	65	6.2
50	70	6.9
67	75	8.0
70	80	10.0
80	85	15.3
85	87.5	25
88	90	56

From these reports, it is obvious that mechanical cooling will be necessary in many areas if prolonged shelter occupancy is to be safe. To date, the majority of study has centered around the 85° F (effective temperature) recommended by OCD. The estimates of ventilation necessary to maintain this temperature limit are related to the ambient weather conditions and other diurnal variations, and it is, therefore, impossible to establish any one criterion. In addition, the results of recent studies indicate that an effective temperature of 85° F may be too high for even young, healthy people to endure over a two-week closure period.[159]

2. External Hazard

The external hazards to be considered for a shelter protecting its occupants against the mass fire environment are heat and fallen debris, carbon monoxide, smoke, oxygen reduction, and noxious gases. These hazards are discussed here individually and as they relate to one another.

a. Heat and Fallen Debris

The heat load placed on the shelter environment by a mass fire is a function of the time-temperature history of the surrounding air, the radiant heat exposure, thermal diffusivity of the shelter structure, and thickness of shelter construction. The surface temperatures adjacent to an actively burning fire might increase rapidly to a high temperature and then gradually decrease with time as the combustible material is consumed, or it may be exposed to burning debris which covers the shelter and causes a long, slow buildup of heat. The free burning fire and its high air temperatures are not expected to exist for more than 4 to 8 hr, while the high temperatures of smoldering rubble may last for days or even weeks.[30]

When the top of a slab or overburden above an underground shelter is blanketed with burning or smoldering material, the lower surface of the slab will progressively rise in temperature and may continue to rise for some time after the fire subsides. The magnitude of the temperature rise at the ceiling of the shelter can be estimated from Figure 26. The assumed fire model for these curves is based upon sudden outside surface temperature rise to fire temperatures, t_f, at time = 0, followed by a linear return to the initial top slab surface temperature before the fire, t_o. The elapsed time is designated as the fire period, θ_o. The temperature, t, of the lower surface of the slab will continue to rise for a time during the postfire period and can be computed from the temperature rise function, ϕ_F, at any time, θ, after the start of the fire. The crest of each curve occurs at the time when the temperature of the lower surface is maximum.[7]

The equations on the following page have been written to express these relationships:

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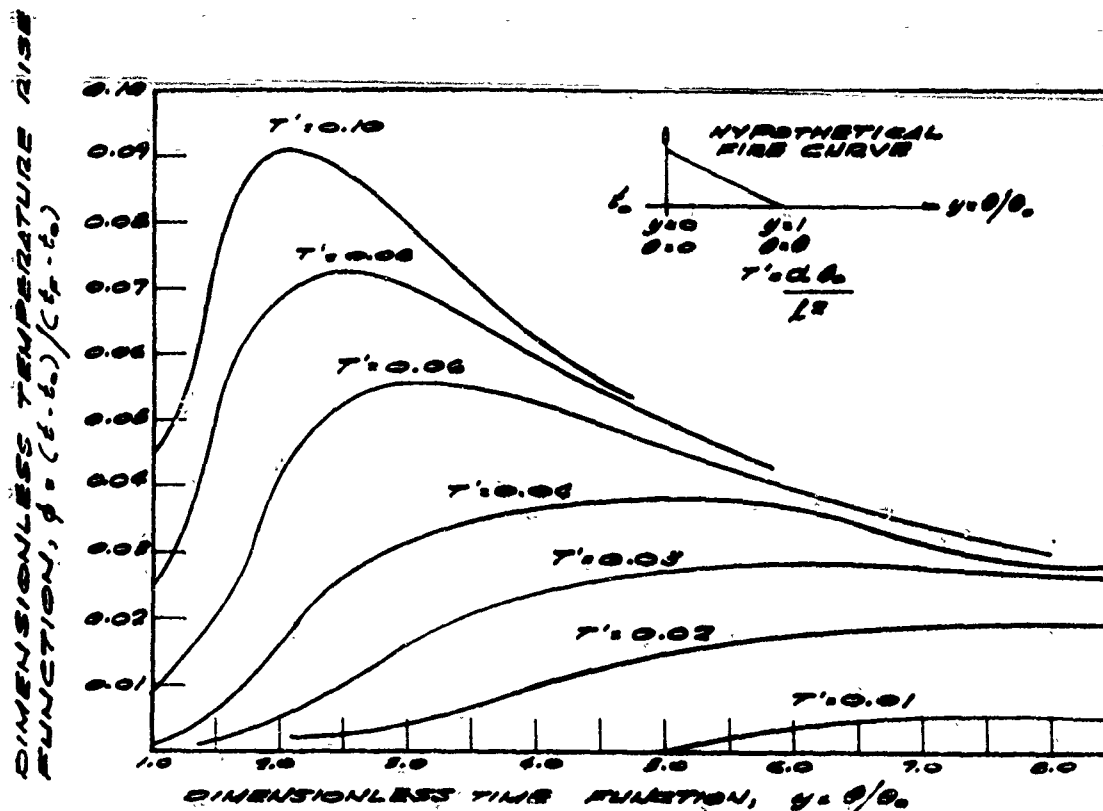
Source: See Ref. (7)

FIGURE 26. TEMPERATURE RISE OF SHELTER CEILING
CAUSED BY AN OVERHEAD FIRE

$$T' = \frac{a\theta_o}{\ell^2} \tag{12}$$

$$\phi_F = \frac{t - t_o}{t_F - t_o} \tag{13}$$

$$Y = \frac{\theta}{\theta_o} \tag{14}$$

where ℓ is the thickness of the slab in feet. For example—to determine the maximum ceiling temperature of a shelter and the corresponding elapsed time from time of fire commencement, when:

(1)   the maximum temperature, t_F, of the external surface of the roof during a fire is 400° C (752° F);

(2)   normal roof temperature is 27° C (80° F);

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(3) the roof is 2-ft thick and has a thermal diffusivity, α, of 0.03; and

(4) the estimated temperature recovery time, θ_0, due to the fire is 8 hours;

the solution is as follows:

$$T' = \frac{(0.03)(8)}{(2)^2} = 0.06 \tag{15}$$

From Figure 26, the peak of the curve occurs at Y = 3.25, the value of θ is determined by

$$\theta = (8)(3.25) = 26 \text{ hr to max ceiling temperature} \tag{16}$$

This example points up the importance of shelter location in regard to the exposures surrounding it.

The most serious hazard is expected to result in those cases where the shelter is buried by heated rubble and exposed to the higher temperatures of 540° to 1090°C (1000° to 2000°F). Using 815°C (1500°F) as the maximum temperature, t_F, of the external surface of the roof during the fire, Eq. (13) then becomes

$$t - 80 = (0.055)(1500 - 80) \tag{17}$$

$$t = 158°F (70°C) = \text{maximum ceiling temperature}$$

Leutz presents similar data (see Fig. 27).

Experience from World War II and peacetime fires indicates that two different burning conditions may be expected depending upon the degree of blast damage. If the structures are left standing while ignited, they will burn freely and tend to collapse straight down into their own foundations. If there is a great amount of structural collapse prior to ignition, these buildings are expected to burn cooler resulting in lower air temperatures; however, they will undoubtedly burn over a much longer period of time. Any shelters covered by such burning debris will be subjected to higher temperatures over a longer period of time than a shelter exposed only to heated air from a short, hot, freely burning fire.

Where shelters are covered by burning debris, the occupants must seek escape as soon as outside conditions permit. For this reason, the exits must be protected from falling debris where its occurrence is possible. Of those that survive the initial mass fire, many will be able to
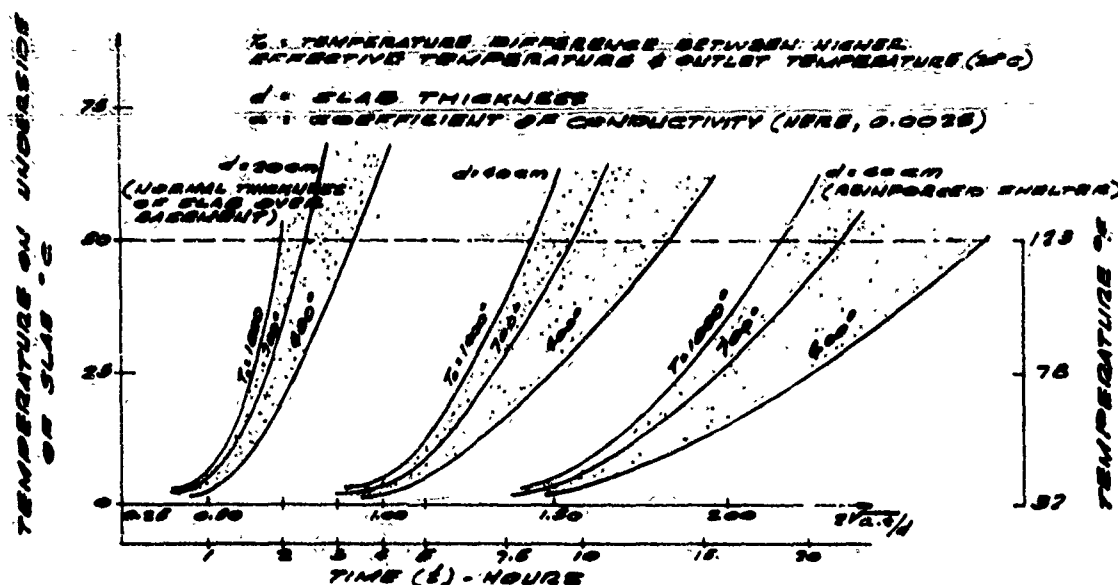
Source: See Ref. (182)

FIGURE 27. HEAT CONDUCTIVITY OF
REINFORCED CONCRETE SLABS

escape by leaving their shelters, while others who cannot leave because of blocked exits will be forced to suffer the slow but steady buildup of heat from the smoldering rubble which may be in direct contact with the shelter envelope.

Experience with blast damage, fires, and smoldering debris in Germany led to the use of protected exits in those areas exposed to rubble.[164] These exits were protected by brick or formed concrete archways which led to an area of safety beyond the reach of falling debris. Studies by Ahlers[3] and Edmunds, et al.[102], have investigated the structural debris caused by nuclear blast and the problems involving in clearing the area after the attack.

  b. Carbon Monoxide, Smoke, Oxygen Reduction,
    and Noxious Gases

The influx of smoke and fire gases into a shelter is perhaps the most difficult hazard to define in the mass fire environment. If the shelter is completely sealed off from the external environment, there is no problem other than the internal buildup of heat and carbon dioxide, the reduction in oxygen, and the external heat load on the shelter envelope. When the conditions inside the shelter approach dangerous limits, there will be a need to get fresh air into the shelter or renew the internal air.

As indicated earlier, heat is expected to be the primary factor leading to the need for ventilation in a closed shelter. When this ventilation is sought, there is the risk of bringing additional heat plus fire gases

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into the shelter. Considering the expected duration of a mass fire in any particular area, the outside air should be in a useable condition after approximately 6 to 8 hr from ignition time. If the shelter is still occupied, the shelterees may elect to leave or to remain in case of fallout. There is also the possibility that their exit may be blocked, preventing their leaving. In either case, if the occupants need fresh air, their lives depend upon the safety of the outside environment.

If the outside air contains high carbon monoxide or a lethal concentration of other noxious gases, ventilating the shelter will bring these fire gases inside. Leaving the shelter will accomplish the same exposure. In this regard, it should be noted that there are no accounts of any persons who were able to survive the firestorms in Germany and then were killed by the lingering carbon monoxide or noxious gases. The only deaths appear to be those which occurred to trapped shelterees subjected to the long heat buildup and to carbon monoxide from smoldering rubble.

In case of internal buildup of heat and carbon dioxide, there is the possibility of being trapped in a shelter without exposure to external heat and carbon monoxide. As suggested by Broido and McMasters[37], a vent located free of rubble should provide the shelter with adequate fresh air to supply the necessary cooling and oxygen until rescue is effected.

The hazard of heat, gases, and smoke is most severe during the active fire burning period including the buildup and burnout periods (approximately 8 to 10 hr). The greatest hazard will of course occur in those shelters that are open and exposed to the wind currents of combustion products. The importance of external wind conditions has been shown by two investigations.[313, 386] Winds of 4 to 50 mph can create pressures of 0.01 to 1.0 in. of water.[132] Thus, it is apparent that enough pressure is available to force combustion products into shelters.

The shelter spaces most exposed to the mass fire environment are those in high rise buildings on the upper floors exposed by plain glass windows. There are also those people who are caught in the open and some who will remain in residential structures. Those in residential structures (wood frame) who seek shelter in basements would not be expected to survive a mass fire that passes overhead.

In order to accurately define the hazard from the influx of combustion products into a shelter, several variables must first be known. These are:

(1) The qualitative composition of the combustion products (carbon monoxide, oxygen, carbon dioxide, etc.),

(2) the quantitative composition of the combustion

(3) wind velocity and direction,

(4) shelter geometry and arrangement,

(5) rate of inflow of combustion products,

(6) shelter size, number of occupants,

(7) shelter ventilation, and the

(8) environmental conditions in a shelter at or before moment of influx.

From this list of variables, it is obvious that a precise definition of the hazard cannot be had at the present time; however, the hazard in general may be recognized and investigated. Items (3), (4), (6), (7), and (8) may be assumed for purposes of discussion at this stage in the "state-of-the-art." Item (5) is presently under study. Items (1) and (2) have received study by several investigators, each in his own way and under varying conditions. Without a precise definition of the ranges of carbon monoxide, carbon dioxide, and oxygen that are contained in the combustion product stream, the life hazard cannot be evaluated.

For this reason, as a part of this project, these two items were investigated under carefully controlled conditions in order to obtain an indication of the ranges of these gases to be expected and their corresponding ratio in regard to each other. This experimental work is presented in Section VII of this report.

One additional item must be considered in order to define the true hazard from the influx of combustion products into shelter spaces, and that is to define the effect of these combustion products on humans. This important item, when defined, will clearly establish the allowable leakage which may be safely permitted into shelters in areas prone to mass fire development.

With development of leakage rates, knowledge of the combustion products, and a definition of their true hazard, the life safety of shelters may be evaluated on a basis never before possible.

Review of the facts known to date indicates that survival is possible within a mass fire environment. It has been estimated that in Hamburg 187,000 out of some 227,000 persons who initially took refuge in the least protective types of shelters ("communal or private cellar shelters") within the firestorm area were "saved either through remaining in the shelters throughout the raid or by escaping to some safer place while there was yet time."[98] Of those who were saved by "escaping to some safer place while there was yet time," some 45,000 did so with the aid of rescue.[98] The few

and simple requirements for life safety within a mass fire have been outlined by several investigators since World War II. The most serious problem in large American cities may be the inability to get enough separation of shelters from rubble in those areas where collapse and burning will occur. In other situations where fires are the main problem, the most serious factor will be the influx of combustion products into the large fire-resistive buildings (both from internal and external fires) established as shelters. In Japan, experience demonstrated that many fire-resistive structures may be completely gutted by fire and left standing as structural skeletons.[144] Such structures, if protected from radiant energies and burning brands, could stand as safe shelters in the midst of a burning city. At the present time, there is not sufficient definition of the mass fire environment to determine the life hazard of combustion products in open areas or at various distances in the air within a mass fire.

In an attack situation where the sheltered populace is subjected to a mass fire and there is no radioactive fallout, it is possible to envision the development of fear from fallout. This could serve to prevent people from escaping shelters which may later be subjected to conditions beyond man's survival limits.

VII. EXPERIMENTAL STUDY OF COMBUSTION PRODUCTS

Several authors have reported on investigations into the generation of combustion products by burning various building materials.[46, 76, 169] Each investigator has established different burning conditions, used different methods, different materials, and reported his data in varying ways. A review of this work, as presented in Section IV, reveals a hodgepodge of experimental data when an attempt is made to relate the results to a mass fire environment.

The difficulty of extrapolating various test results has been recognized by many authors. These problems are understandable when one considers the tremendous difficulties posed in conducting actual large-scale experimental fires. There are many variables, and it is nearly impossible to hold some of the parameters fixed so that valid comparisons can be made. As a result, the reports of the various investigators indicate a wide range for each of the parameters of interest which cannot be related to any one of or to a combination of variables.

For this reason, it was decided to establish a burning condition for a typical building material and conduct a limited number of experiments utilizing a standard test facility and with ventilation as the only variable. In this manner, the production of heat, smoke, flame and toxic gases could be directly related to the rate of ventilation and to each other, under the precise conditions of each test. As a result of his work, Zapp[386] stated that the rapid death which can occur as a result of exposure to conflagrations "may be due to heat or to the inhalation of a toxic atmosphere or to a combination of these. Ventilation determines which of these factors predominate."

Data thus secured would provide basic information regarding the amounts of heat, smoke, and toxic gases to be expected from burning a combustible building material under varying ventilation conditions and their relative production rates with respect to each other. Such data could be used to approximate the conditions of exposure to people in mass fires. Further research would then be necessary to define the life hazard presented under the range of conditions to be expected. This combustion study is a necessary and basic step required in the full definition of the mass fire life hazard.

In an effort to examine more closely the importance of ventilation in the production of combustion products, a series of experiments were conducted utilizing the 25-ft flame spread tunnel furnace—ASTM E84-61 "Standard Method of test for Surface Burning Characteristics of Building Materials." In this test, a sample 20 in. wide and 25 ft long is mounted on the top of the furnace, and the underside of the specimen is subjected to an ignition flame at one end, while the rate of airflow along the length of the sample is carefully controlled. Under normal test conditions, the various building materials are exposed to an ignition flame burning approximately 4-1/2 cu ft of natural gas/minute while the airflow is

maintained at 240 feet per minute (fpm). In the tunnel furnace, which is approximately 18 in. wide by 12 in. high in inside dimension, this amounts to an airflow of 360 cfm. The air is controlled throughout the test to maintain a constant turbulent flow.

During each test, the specimen is monitored visually for the spread of flame along its surface; the heat output is monitored by means of a thermocouple placed in the exhaust stream; and the smoke production is monitored by a photocell placed in a vertical position in the downstream exhaust duct. The tunnel furnace is shown in Figure 28.

Source: SwRI

FIGURE 28. ASTM E-84 TUNNEL FURNACE

In addition, during these tests, the exhaust stream was continuously monitored for its oxygen, carbon monoxide, and carbon dioxide content. The carbon monoxide and carbon dioxide were monitored continuously by means of two Beckman Model 315 infrared analyzers, and the oxygen was continuously monitored by a Beckman Model F3 oxygen analyzer utilizing the paramagnetic properties of oxygen. Figure 28 depicts the gas analysis apparatus. The gas analyzers sample the combustion product stream at a point approximately 14 ft downstream from the end of the furnace, and the ductwork is fully insulated throughout this portion.
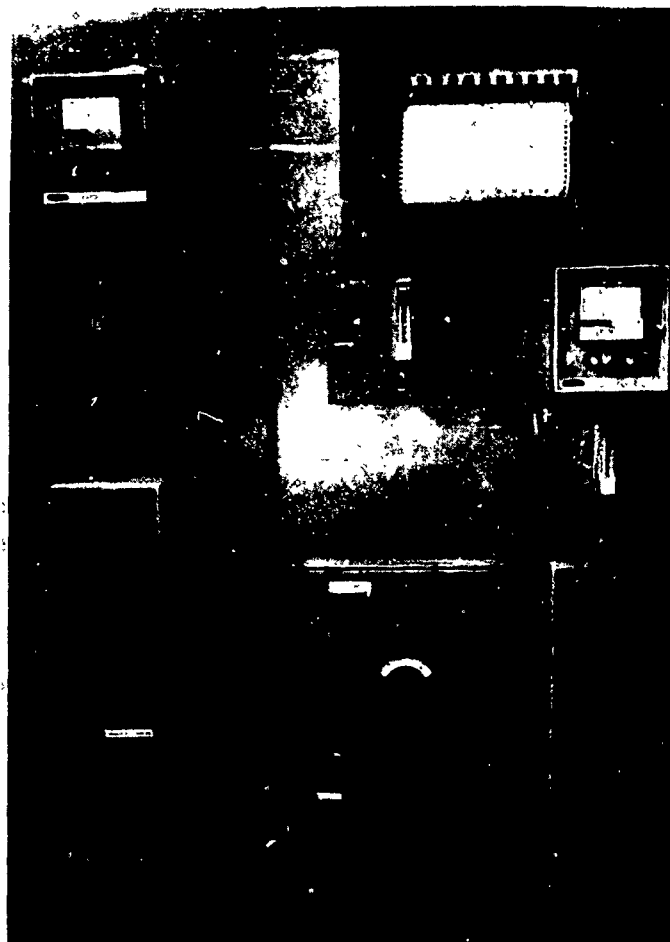
Source: SwRI

FIGURE 29. CARBON DIOXIDE, OXYGEN AND
CARBON MONOXIDE ANALYZERS

Since the purpose of this investigation is the definition of the mass fire life hazard, it was decided to evaluate the effect of ventilation on the combustion products produced by ordinary building materials using the 10-min fire test to answer questions such as: How low does the oxygen fall? What range of carbon dioxide can be expected? What range of carbon monoxide can be expected? and, What are the ratios of these parameters with each other? The synergistic relationship and its importance has been recognized but lacks the necessary definition to evaluate the life hazard.

In order to examine the ranges of the parameters to be expected and their ratios with each other, it was decided to concentrate on one common building material and burn it in a controlled manner under varying airflow conditions. Untreated and uncoated Douglas fir was chosen because of its wide use in construction. The production of combustion gases, smoke and heat were monitored under airflows of 100, 200, 240 (the standard velocity),

300 and 400 fpm in each of five separate tests. The results are shown in Figure 30 and indicate the following general conclusions:

- Smoke production varied with the velocity. As the velocity increased, the smoke production (light absorption) decreased. At 100 fpm, the light absorption reached a high of 18 percent which was considerably higher than measured in all four other tests which ranged from near zero to 5 percent.

- The temperature of the exhaust gases reached a peak at 240 fpm which was obviously an optimum burning condition. At 240 fpm, temperatures reached 605° C (1125° F), and, at 100 and 400 fpm, they reached 325° and 280° C (615° and 530° F), respectively.

- The degree of oxygen reduction recorded in the combustion product stream increased as the velocity decreased. At 100 fpm, the oxygen content was reduced to 13 percent, and, at 500 fpm, reached a low of 19 percent.

- The carbon dioxide concentrations recorded in the effluent stream followed a pattern similar to the oxygen reduction in that it increased as the flow decreased. A maximum of 5.3% was recorded at 100 fpm and a maximum of 1.3 percent at 400 fpm.

- The carbon monoxide concentrations recorded in the effluent increased from 0.05 percent at 400 fpm to 1.0 percent at 100 fpm.

Considering the carbon dioxide/carbon monoxide ratio as an indication of the type or completeness of combustion, Figure 31 was plotted. The carbon dioxide/carbon monoxide ratio varied from 6 to 30, increasing as the airflow increased. Here, carbon dioxide is an indication of complete combustion, and carbon monoxide is an indication of incomplete combustion.
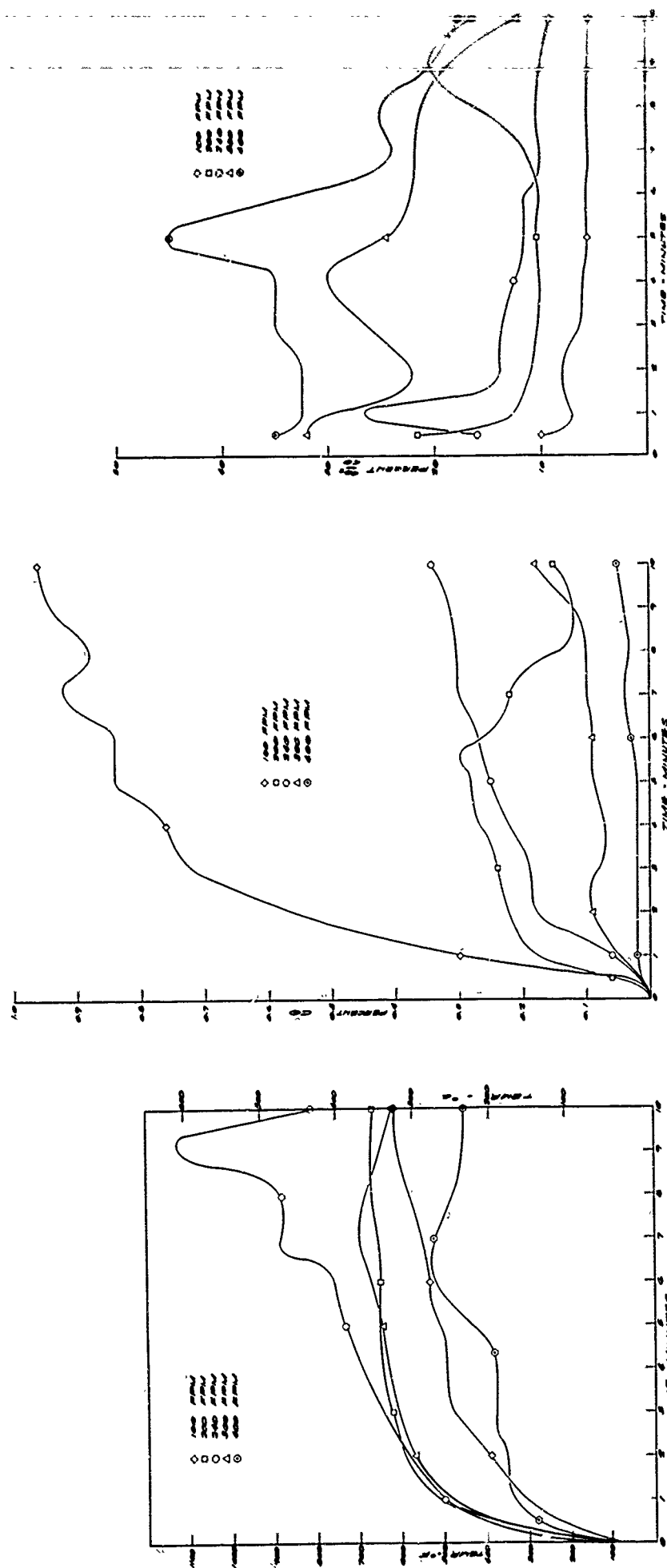
These results indicate that an optimum burning condition exists somewhere near the 240-fpm flow rate. The fact that 240 fpm is the standard flow rate chosen also indicates its optimum qualities. At flow rates above 240 fpm, the specimen burns more cleanly, produces less smoke, less carbon dioxide and less carbon monoxide (percent by volume) and reduces the oxygen content of the combustion product stream by a lesser amount.

An airflow of 240 fpm produces the hottest fire, and airflows above and below 240 fpm produce much cooler fires. However, when examined more closely from the standpoint of total heat content, the area under a time temperature curve may be integrated to reveal a different relationship.
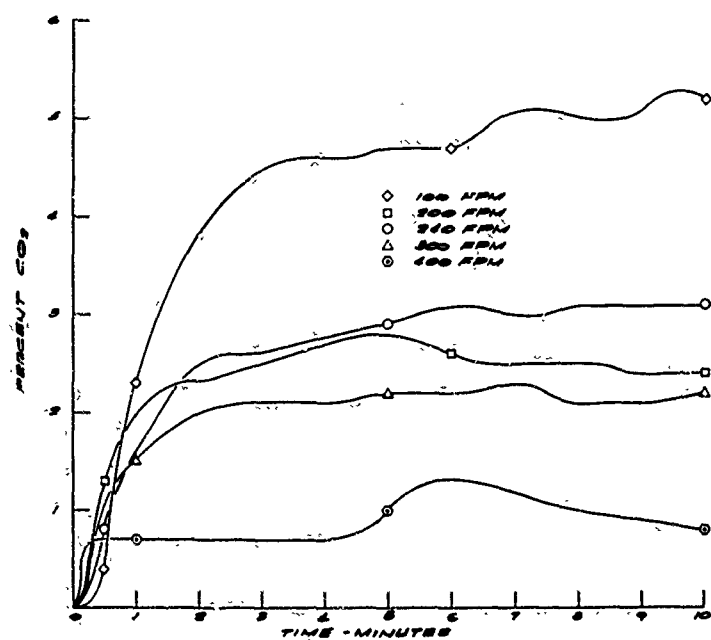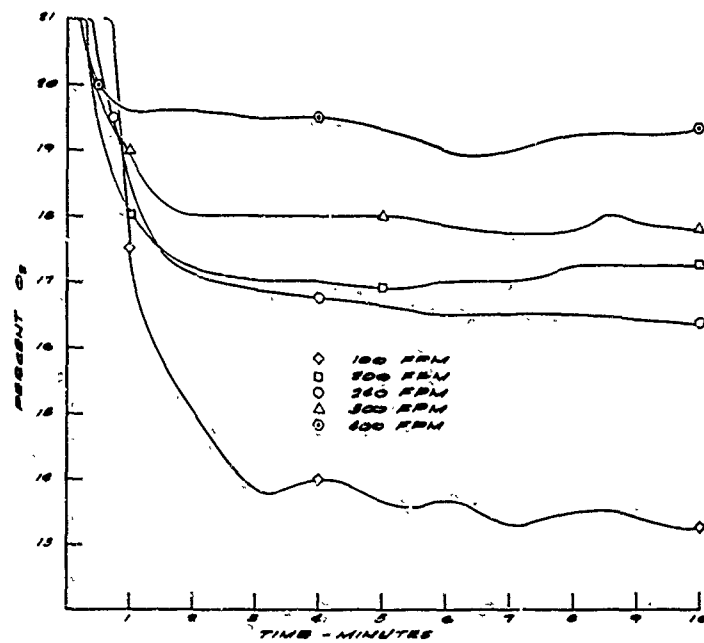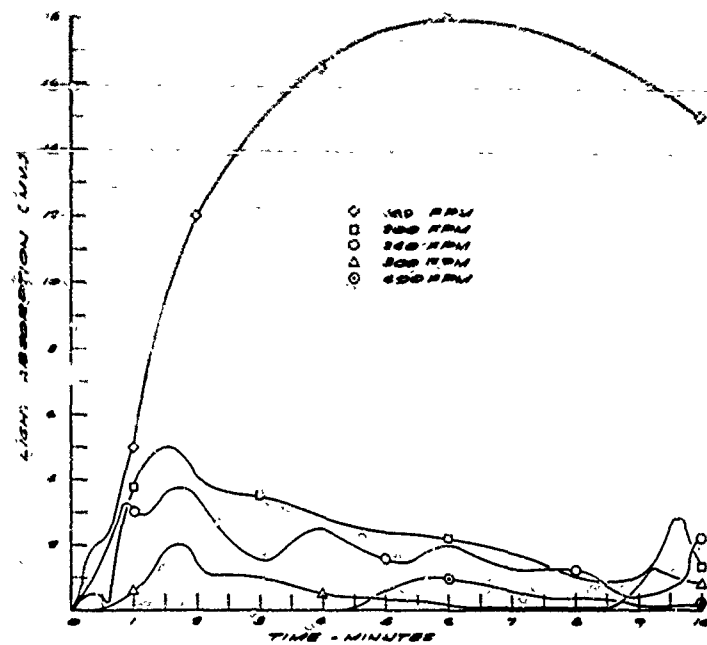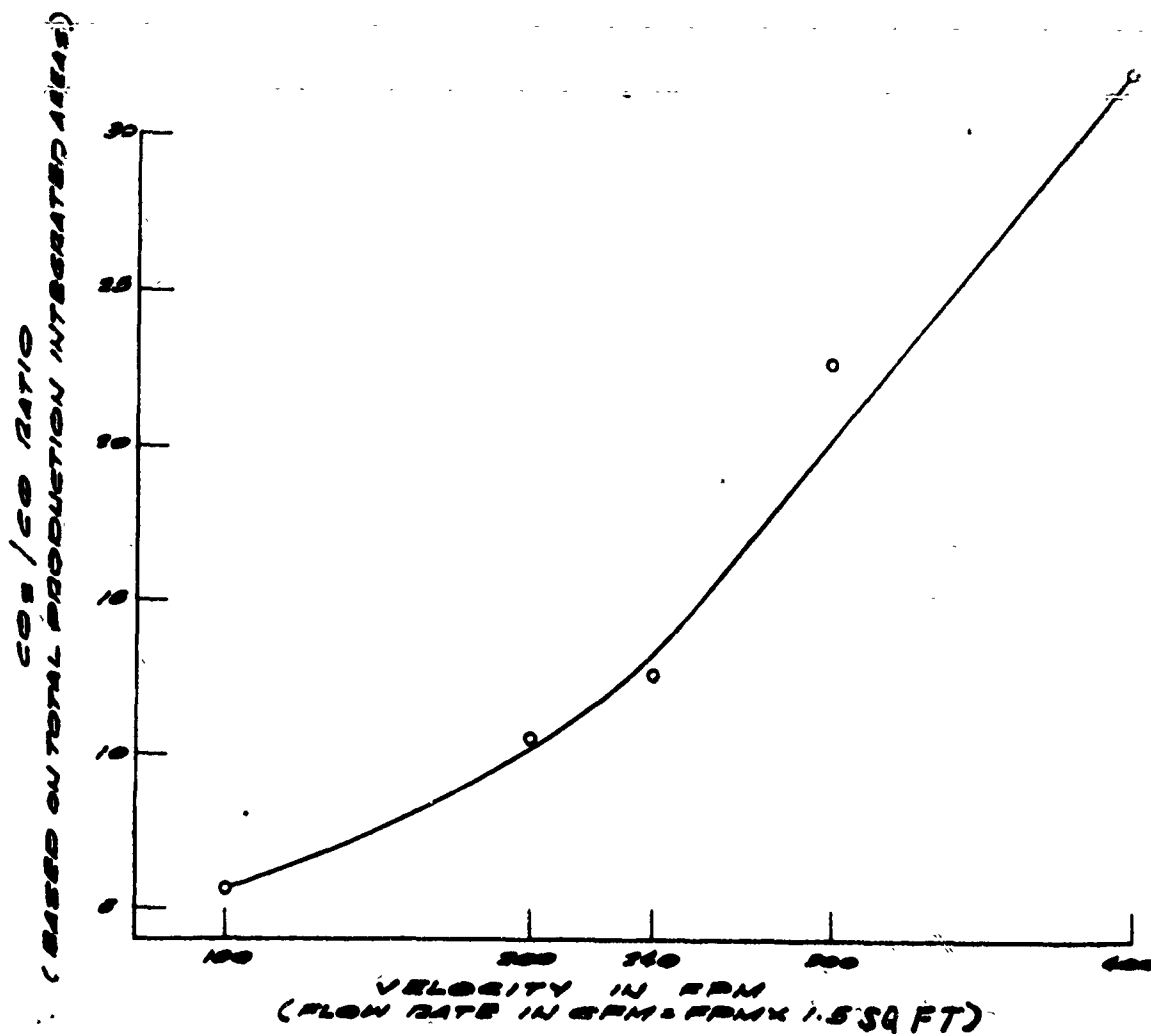
Source: SwRI

FIGURE 30. COMBUSTION PRODUCTS GENERATED
UNDER VARYING VENTILATION

FIGURE 30. COMBUSTION PRODUCTS GENERATED
UNDER VARYING VENTILATION (Cont'd)

Source: SwRI

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Source: SwRI

FIGURE 31. CARBON DIOXIDE/CARBON MONOXIDE RATIO
OF COMBUSTION PRODUCTS

When these results are plotted as in Figure 32, the results look different since the total heat production does rise as the airflow rises. Although the temperature falls, the increased airflow more than makes up the difference in terms of total heat.

The production of carbon dioxide and reduction of oxygen actually follow an inverse pattern when compared with heat production. The specific concentrations (percent by volume) of carbon dioxide and reduction in oxygen (cu ft) are at a maximum at 240 fpm (see Fig. 32). The total production of carbon monoxide was not a maximum at 240 fpm.

These figures confirm the fact that the maximum total production of carbon dioxide and maximum oxygen reduction occur at the peak burning temperature. The instantaneous maximums of gas concentrations in percent by volume all occurred at the lowest airflow.
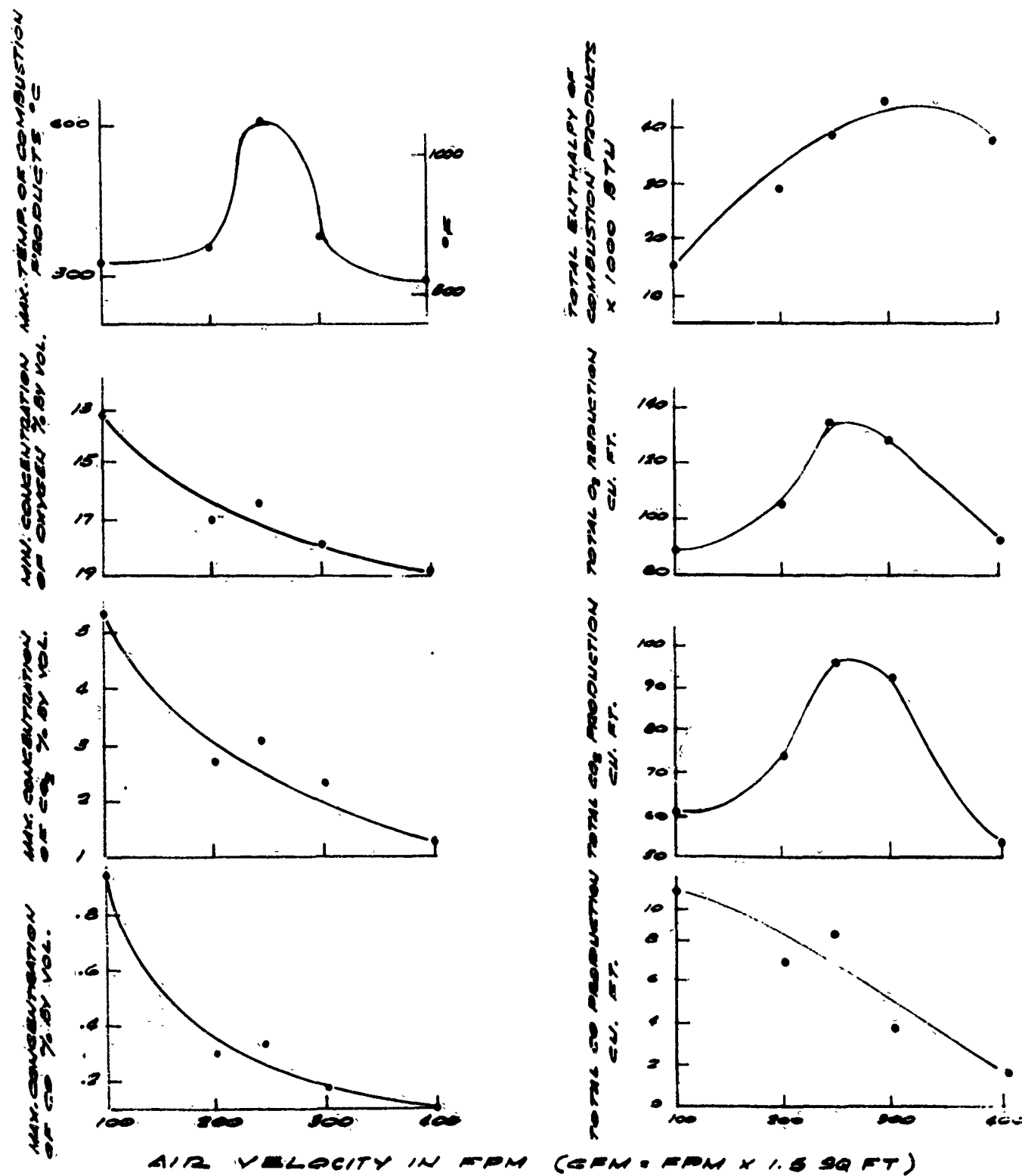
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FIGURE 32. RELATIONSHIP OF COMBUSTION PRODUCTS
TO VARYING VENTILATION RATES

The momentary carbon dioxide/carbon monoxide ratio varied between 6 and 30 with a general relationship throughout the tests of lower ratios at lower airflows. The ratio of total carbon dioxide/carbon monoxide production is also nearly a straight line function of airflow with high ratio at high airflows and low ratios at low airflows (see Fig. 31).

Life safety in a mass fire can be evaluated if the exposure to the significant combustion products is known. If the exposure is not known, then it must be assumed, and this work provides a basis for those assumptions.

The data reported herein reflect only the combustion products that would be produced from ventilated fires. This work should be extended to investigate the effects of lowering the ventilation rate to near zero in addition to tests utilizing other common building materials.

With these data, a hypothetical mass fire situation may be evaluated in terms of life safety. A burning condition may be assumed under particular ventilation conditions. This combined with a known leakage rate will allow calculation of the gas concentrations to be found in the shelter.

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VIII. EXPERIMENTAL STUDY OF THE EFFECTS OF COMBUSTION PRODUCTS

A. General

As a part of this contract, an attempt was made to conduct a modest but carefully controlled series of animal tests to form a partial basis for determining the life-safety hazard. Those parameters which are strongly indicated as the primary factors in the cause of fire-related deaths by many investigators[37, 95, 385, 386] were studied.

This parametric analysis is intended to point up the relative life hazard as presented by each parameter. In addition, and most important, the study is intended to define the synergistic relationship of each factor with every other and the synergism presented by a combination of all factors.

It was decided to investigate only those parameters which have already been singled out as of primary concern by past investigators. These factors include heat, carbon monoxide, and oxygen (reduction). The effects of other trace constituents were not studied in the current program. However, they should be considered in order to determine the magnitude of the respiratory tract injury problem; i.e., it may be the combination of all the trace gases (aldehydes, ketones, nitrous oxides, etc.) that is the significant factor. To define the scope of the problem, it is important that this relationship be known. The importance of smoke (airborne particulates including carbon and any gases that may have condensed on the cooler particles) is one other factor in need of definition.

The initial study begun during this year's work was designed to provide the basis for the demonstration of the significance of the total combustion product stream from one common building material in relation to an exposure at the same temperature and carbon monoxide level. Animals were exposed to a controlled temperature environment in the laboratory at various levels of carbon monoxide in air. These results now form the basis for comparison of an exposure to a stream of combustion products from the burning of a common building material. The stream could be sampled at the precise time it contained the desired amount of carbon monoxide and the temperature easily controlled to any desired level. The results of such a test should indicate the significance of the effect of the entire combination of noxious gases as opposed to the effect of carbon monoxide by itself.

A work plan such as the one briefly discussed is designed to define the relative importance of the now known primacy factors in the mass fire environment. The end result of such work should be the development of time-concentration values of the primary factors and their effect on humans. Such a plan should also define the significance of trace gases and smoke.

B.   Study of Mice Exposed to Moderate Variations in Temperature and
Carbon Monoxide

As a first step in the previously described plan, white mice were
exposed to variations in temperature and carbon monoxide concentrations in
air to determine the significance of any synergistic action that might result.

These experiments were conducted in the SwRI laboratories by quali-
fied personnel in the Department of Physical and Biological Sciences under
the direct supervision of the Manager of the Analytical and Biochemistry
Section.

1.   Animals

The test animals used were adult male, Swiss albino mice, 25
to 30 grams. The animals were procured from Simonson Laboratories, Inc.,
Gilroy, California.

2.   Test Apparatus

An exposure chamber of approximately 1-cu ft volume was con-
structed of plastic as shown in Figure 33. The chamber included an electrical
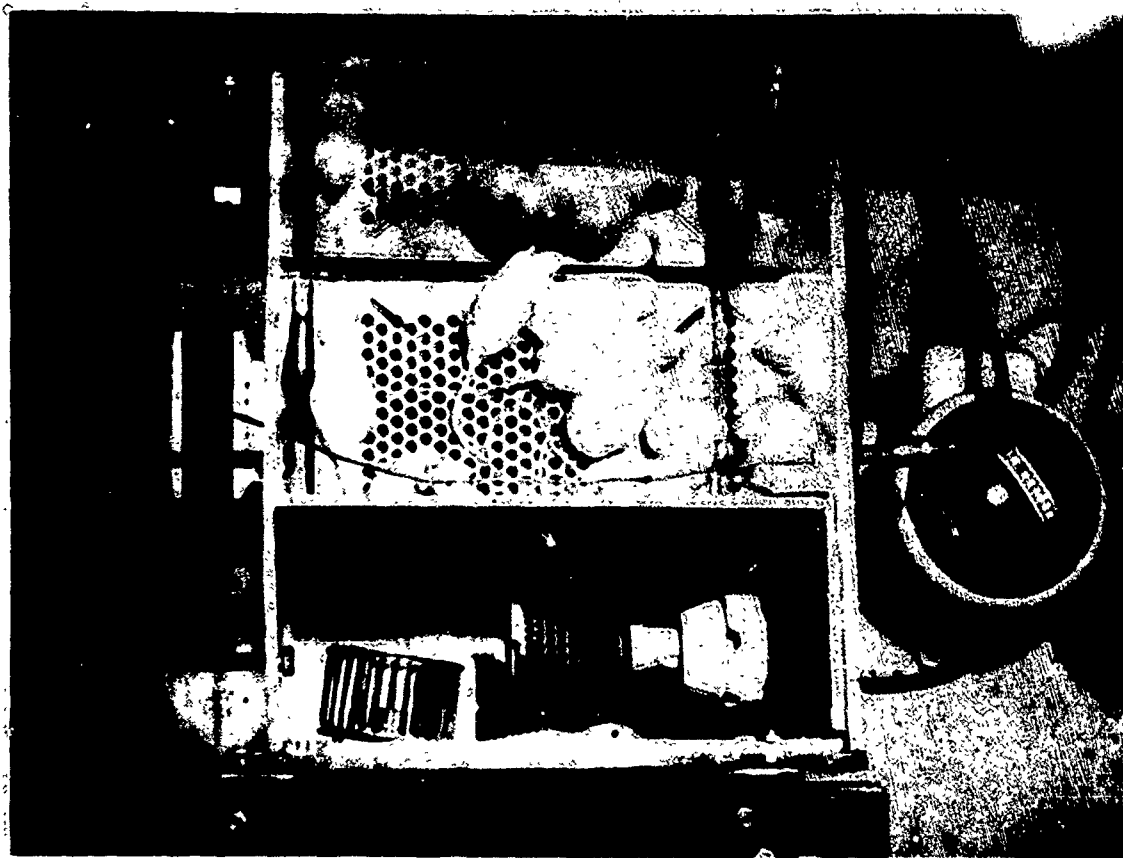
Source: SwRI

FIGURE 33.   VIEW OF ANIMAL EXPOSURE CHAMBER
WITH TOP REMOVED

(cone) heater and fan controlled by a rheostat, thermometer, and relative humidity indicator. The area housing the heater and fan was separated from the animals by a perforated asbestos sheet.

Carbon monoxide and breathing air was directed through individual flow meters into a mixing chamber and then into the exposure chamber. The gas concentration in the chamber was then monitored for its carbon monoxide content by a Fisher gas partitioner (Model 25V), modified to allow a preset aliquot (5 to 565 ml) of chamber gas to pass through to a manually controlled integral gas sampling valve and then through a molecular sieve chromatographic column. Signals from the thermistor detectors were then transferred to a Servoriter recorder (1 millivolt, Texas Instruments, Inc.). Carbon monoxide concentrations were calibrated and monitored on the basis of peak height only.

This Fisher gas partitioner was also calibrated against a Beckman Model 315 infrared analyzer calibrated in the 0- to 2-percent carbon monoxide range. The agreement at levels of 0.05, 0.10, 0.30, 0.50 and 0.74 percent were checked, and the greatest deviation was found to be 0.02 percent. The deviation at 0.05 percent was only 0.003 percent; average deviation was 0.011 percent. A schematic outline of the test apparatus is shown in Figure 34.
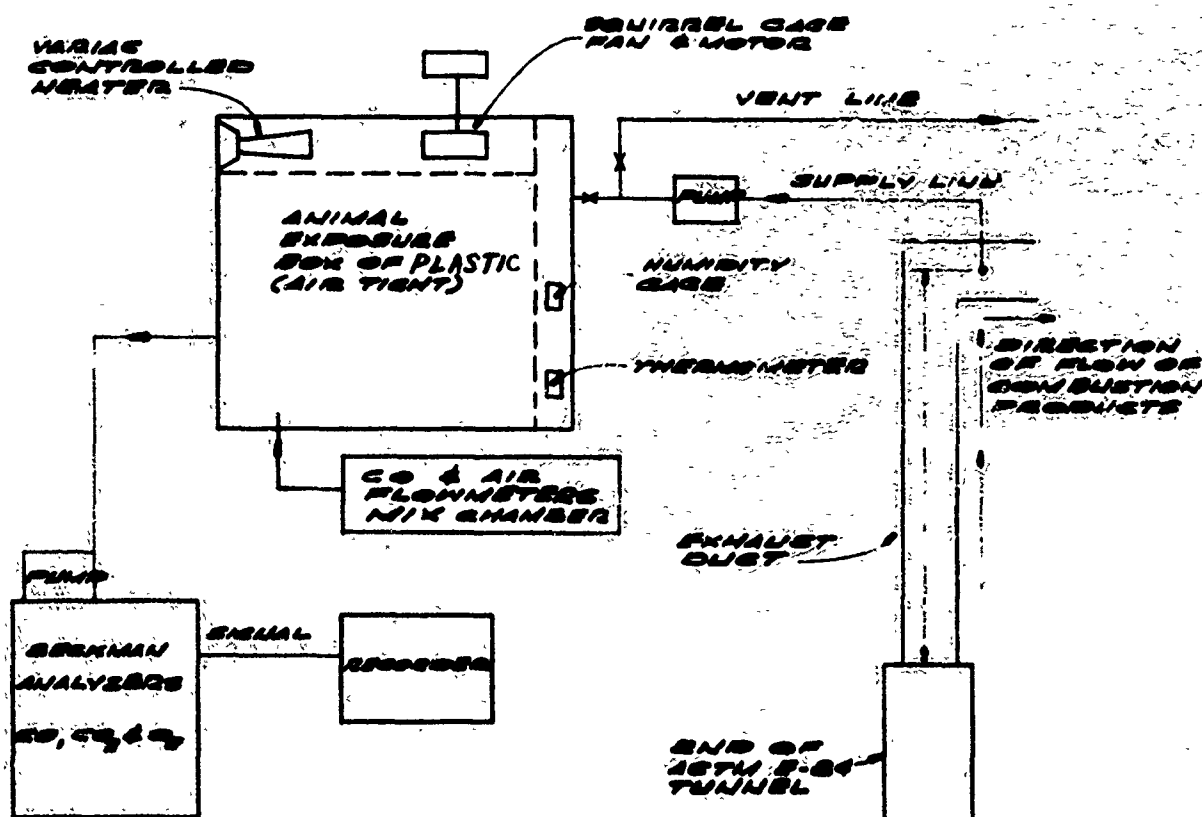
Source: SwRI

FIGURE 34. SCHEMATIC OF ANIMAL EXPOSURE APPARATUS

Each test was conducted with ten animals which were selected without sorting from stock, placed in a clean group cage with standard laboratory food and water, ad libitum. The animals were allowed to acclimate for not less than 1 hr prior to testing. No survivor of any test was utilized again. All work conducted was in compliance with the "Principles of Laboratory Animal Care" established by the National Society for Medical Research.

3.   Observations

Test animals exposed to temperatures of 38°C (100°F) or higher temperature (with or without carbon monoxide) for over 1 hr showed an obvious pattern of activities and reactions including exploring, nose rubbing, jumping (escape attempts), increased respiration, increased heart beat, defecating, micturating, decreased respiration, decreased heart beat, lethargy and then death. Those exposed to 38°C (100°F) for 1 hr with no carbon monoxide did not die. The animals exposed to carbon monoxide at 27°C (80°F) showed some similar but not identical reactions including exploring, lethargy, decreased respiration, decreased heart beat and then death.

From experience, the time of death was noted to be that point where respiration and heart beats were no longer visible. The results of the tests are shown in tabulated form in Table 23.

These results indicate that temperatures of 38° and 49°C (100° and 120°F) are quite severe on the mice and do tend to overshadow any effect of low levels of carbon monoxide on the animals. There does appear to be sharp effect of heat somewhere between 27° and 38°C (80° and 100°F).

The results from the tests at 27°C (80°F) and 38°C (100°F) suggest that there is a significant synergistic effect between carbon monoxide and heat. At 27°C (80°F) with 0.5 percent carbon monoxide in air, the ten animals survived an average of 0.88 hr in the chamber. At 38°C (100°F) and no carbon monoxide, the animals survived an average of 1.6 hours. When exposed to a combination of the two, i.e., 38°C (100°F) and 0.5 percent carbon monoxide in air, the animals survived an average of 0.13 hr in the chamber. This is a reduction in the average time of death of over 670 percent-a very significant effect.

A control experiment was later run at 27°C (80°F) with no carbon monoxide, and the animals survived a full 10-hr exposure in the chamber.

TABLE 23. EFFECTS OF TEMPERATURE AND CARBON MONOXIDE ON WHITE MICE (Time of Death in Min)

Temp. °C	27°C	38°C	38°C	47°C	49°C	27°C	38°C	49°C	27°C	38°C	49°C	27°C	38°C	49°C	27°C	38°C	49°C
Temp. °F	80°F	100°F	100°F	116°F	120°F	80°F	100°F	120°F	80°F	100°F	120°F	80°F	100°F	120°F	80°F	100°F	120°F
% CO	None	None	None	None	None	0.05	0.05	0.05	0.1	0.1	0.1	0.3	0.3	0.3	0.5	0.5	0.5
Humidity[1]	None	20/65	85/60	80/82	50/68	24/50	30/80	60/80	50/40	34	55/70	30/40	38/40	52/60	40	60/65	70/40
Animal No.																	
1	(2)	(3)	60	12	13	180	61	12	71	11	10.5	19	10	8	5	3	2.5
2	-		67	14	14	206	70	13	78	12	11	26	10+	9	8	5	2.5
3			75	17	15	214	82	14	127	12.5	12	31	10+	10	15	5	3
4			89	18	15	(5)	85	14	185	14	12.5	38	10+	10	22	6	3
5			91	20	17	-	89	15	222	19	13	61	11	10.5	58	6.5	4
6			93	21	17	-	91	16	255	21	14.5	65	12	11	82	7	5
7			104	23	18	-	102	17	279	21	23.5	67	12	11	83	8	6
8			104	27	18	-	104	18	299	24	28	92	14	12	84	11.5	7
9			117	27	19	-	141	18	304	27	30	95	16	12	87	12.5	8
10	-	(4)	158	27	19	-	160	20	310	36	38	132	20	18	90	13	9
Average			96	21	16		98	16	213	20	19	63	12	11	53	8	5

(1) Relative humidity recorded at beginning and end of each test.
(2) All animals survived 10 hr in chamber.
(3) All animals survived 1 hr in chamber.
(4) One animal expired 42 hr after exposure.
(5) Animals 4-10 survived 4 hr in chamber and 16+ postchamber hours. No apparent abnormal reactions.

Source: SwRI

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IX. CONCLUSIONS

This review of the state-of-the-art of efforts to define the life hazard in mass fires leads to the conclusions presented below:

General

(1) Mass fires, both conflagrations and firestorms, are as yet not well defined in terms of wind patterns, pressures, rate of spread, or temperature profile.

(2) The nature of combustion products in open areas within a mass fire is virtually unknown in terms of both concentration and time.

(3) The protection to be offered within a mass fire environment from the heat, noxious gases, and smoke by various shelter configurations (both designated and nondesignated) is not known specifically. Fallout shelters, as such, cannot be expected to afford protection against mass fires.

Effects of Combustion Products

(4) The preponderance of opinion t   ate recognizes heat, carbon monoxide, and possibly anoxia as the primary causes of death in mass fires.

(5) Heat is considered to be of primary importance in the open. In those shelters exposed to burning or smoldering combustible material, both carbon monoxide and heat are considered to be of primary concern. In a sealed shelter, internal buildup of carbon dioxide can become a serious hazard.

(6) The physiological effects and man's limitations to short term exposures of carbon monoxide and anoxia are fairly well established; however, the effects or limitations of long term, chronic exposure to carbon monoxide and anoxia such as might be experienced in a shelter stay of 3 to 14 days is not clearly established.

(7) The presence of noxious gases and particulate matter in the combustion products from burning materials has been well recognized by many investigators; however, their presence in the mass fire environment and resultant effect on people exposed is virtually unknown. In this regard, the possible synergistic effect of smoke and noxious gases in combination with the well recognized hazard of carbon monoxide, heat, and anoxia has been considered by many investigators and even demonstrated

experimentally by a few. The true significance of such syner-
gisms has not been defined for any combination of factors, even
the commonly recognized "primary" parameters such as heat,
carbon monoxide, and anoxia.

(8) To date, the primary hazard of smoke has been recognized as
visual obscuration. Significance of smoke in inducing panic and
its physiological effect when inhaled or ingested has not been
studied, but it is suspected by some to be a serious factor.

(9) It is extremely difficult to draw any final conclusion as to the
cause of death in past fires as a result of the analytical methods
used in autopsies. Many deaths are determined to be the result
of carbon monoxide poisoning without considering the possible
presence of other noxious gases or substances. In addition,
the respiratory tract has not been carefully studied in such
victims to determine the cause and effect of any chemical
tracheitis that may be present.

X. RECOMMENDATIONS

Further study is required to establish the life hazard within the mass fire environment. The following recommendations are presented to accomplish this objective.

Recommendation No. 1. Studies to Further Define the Mass Fire Environment

There is need for more information on the nature of mass fires, including wind patterns, pressures, temperature profiles and gases. It is recommended that controlled large scale burns of buildings or simulated buildings be developed for this purpose. As an alternate, it is recommended that attention be given to the application of modeling techniques for the study of mass fires. Combustible models, appropriately scaled, should be used so that all parameters of the problem could be studied.

Recommendation No. 2. Study the Production and Composition of Combustion Products

Because of the complex nature of combustion products from the burning of building materials, little is known concerning the environment to be found within a mass fire. Therefore, a study is recommended to determine the makeup of combustion products, both qualitative and quantitative, to be found in a typical mass fire environment in relation to time. Of particular interest in such a study would be the production of smoke, its measurement, and definition.

It is recommended that this study be first conducted utilizing laboratory facilities which are available. Combustion conditions are reasonably reproducible from one run to another which gives a convenient method of making duplicate runs. In such tests, it is recommended that a single variable such as ventilation be utilized to vary the burning conditions and resultant combustion products.

Recommendation No. 3. Study the Hazard of Chronic Exposure to Carbon Monoxide and Anoxia

Data regarding physiological effects of human exposure to carbon monoxide and anoxia over extended periods of time are not available which can be used to define their effects on people in shelters for periods up to 14 days. For this reason, an animal study is recommended to define the threshold limits of carbon monoxide and anoxia for long term, chronic exposures to man.

Recommendation No. 4. Study the Hazard of Combustion Products through Animal Tests

Studies of the physiological effects of combustion products such as carbon monoxide, heat, and anoxia have in the past been defined separately. A program is recommended to study the significance of any synergistic action that may result from a combination of two or more of these variables. This study should include the effects of smoke and any other significant noxious gases to be found in the first part of these recommendations. In addition, the study should define the importance of a stream of noxious gases, each of which may be insignificant by itself, as a whole in combination with the recognized carbon monoxide, heat, and anoxia hazard.

It is not suggested that precise relationships be established but that only the significance and order of magnitude of the various relationships that may exist within a mass fire environment be defined. In this manner, the more important synergistic relationships can be identified and evaluated for further study if necessary.

Recommendation No. 5. Analysis of Body Tissue and Blood

The causes of death to burn victims have been of great concern to medical science, and several investigators have suggested possible reasons for these recurring deaths. These suggestions, based on years of experience, have been made only to encourage further study of recognized problem areas. The most widely recognized cause of death in fires, other than external burns, is the inhalation and ingestion of combustion products which include all types of noxious gases and smoke (particulate matter). A program is recommended in conjunction with the previous two recommendations to investigate the effects of combustion products on the respiratory mucosa and lungs of animals after carefully controlled exposures. Such histopathological studies will determine if any chemical tracheitis or pathological change has taken place. Such a program or study could be undertaken on a national basis with the cooperation of hospitals, burn centers, coroners, medical examiners, and others concerned with the treatment and autopsies of burn victims.

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13 ABSTRACT

A program was undertaken to define the life hazard in a mass fire environment resulting from nuclear attack. The nature of casualties and hazards in peacetime and wartime fires was reviewed, and experimental efforts to simulate mass fire situations were studied.

This state-of-knowledge review revealed a number of areas in need of further definition regarding the true mass fire life hazard. These areas have been specified and limited experimental studies conducted in two of them in order to define their significance with respect to the overall mass fire life hazard.

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MASS FIRE LIFE HAZARD

By A. J. Pryor and C. H. Yuill
Southwest Research Institute
September 1966
OCD Work Unit 2537A
Detachable Summary

Definition of the mass fire life hazard involves many factors and cannot be stated simply in any quantitative manner. This report is a qualitative description of the hazard as it is known to date.

The first part of this program consisted of examining the life safety problem in various possible fire environments by means of a state-of-knowledge review. It indicates quite clearly the generally recognized hazards. Many investigators have defined these as carbon monoxide, heat, and inadequate oxygen by themselves or in combination depending upon the ventilation conditions. Others conclude generally that the important factors are heat in open areas and carbon monoxide in shelters and that deaths occurred only in those shelters directly exposed to burning or smoldering fuel, sometimes in the form of rubble or debris.

Two recent studies are referenced in which a comprehensive review of the literature relative to combustion products in fires in buildings is presented. Both conclude that carbon monoxide and possibly oxygen deficiency are the primary factors in most building fires. Reference is made to the serious effect of the combination of two or more gases each of which if existing alone may not be harmful.

The interrelationships in the development of carbon monoxide, oxygen deficiency, and other gases, or the possible existence of undetermined synergisms have not yet been defined. Also, medical research indicates the importance of respiratory tract injury as the primary killer of the burn patient, yet there is not sufficient information available to analyze the factors involved in respiratory tract injury. No experimental work has been done on inhalation injuries from combustion products in the upper and middle respiratory tract. The chemical tracheitis is not expected to occur from the inhalation of carbon monoxide, a reduced oxygen atmosphere, or even heat. Noxious gases and smoke are suspected as the cause. Heat may be a factor in causing mucosal injury or enhancing it in the presence of carbon monoxide or other noxious gases.

The life hazards and physiological effects of carbon monoxide, heat, and reduced oxygen have been reasonably well defined for fires in individual buildings; however, a true definition of the mass fire life hazard requires that the effects of these factors in combination be known. The literature reveals very little on this subject that is applicable to the mass fire life hazard.

A limited number of animal experiments were performed to examine the significance of any relationship between carbon monoxide and heat. It is indicated that such a combination may be five to twelve times more lethal than either factor considered separately.

A series of animal experiments is recommended to demonstrate the significance of the noxious gases and smoke in a heated stream of combustion products from the burning of typical building materials. Such a program would either confirm or disprove the preponderance of opinion that carbon monoxide, heat, or anoxia are the main hazards in mass fires.